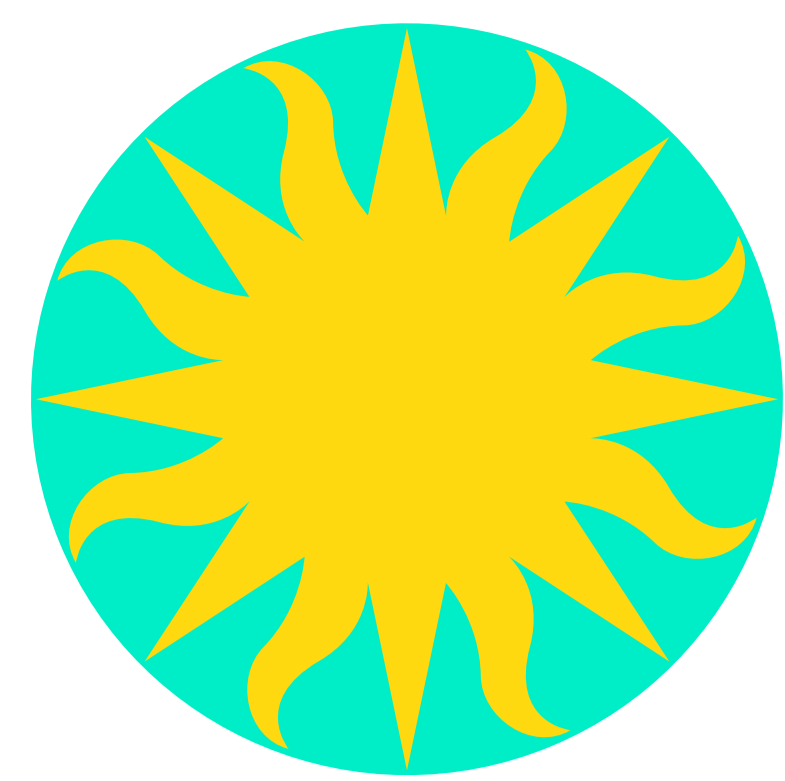


Analytic and Numerical Modeling of Asymmetric Molecular Line Profiles

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Abstract

We present analytic models of spectral line profiles with “infall asymmetry”, suitable for least-squares fitting. We assess their effectiveness in estimating molecular cloud infall properties by comparing them with more detailed models of infalling cloud cores whose molecular line emission is derived using Monte Carlo radiative transfer methods. Our analytic models include both the two layer model (Myers et al. 1996) and a new model which includes linear excitation temperature gradients which we dub the “hill” model. We construct physical models of cloud infall and calculate their molecular line emission for HCO^+ using the Hogerheijde & van der Tak (2000) 1-D radiative transfer code. We then fit those spectra using our analytic models and compare the input and output values of the infall speed and velocity dispersion.

We find that the analytic models often reproduce the numerically modeled spectra very well, even when the analytic cloud structure does not match the numerically modeled cloud structure. The infall speed and velocity dispersion of the analytic models match those of the numerical models, with in a few hundredths of a km s^{-1} , provided the numerical models have sufficiently simple density and velocity fields. The hill model provides a better match to infall speeds, and is less ambiguous than the two-layer model.

Analytic Models

We have developed two analytic radiative transfer models of infall, which can be quickly and easily fit to asymmetric line profiles. From these simple models we can extract physical parameters, such as the infall speed, optical depth, and excitation temperature. We undertake this study in order to evaluate the efficacy of the simple analytic models to recover the physical parameters of more realistic infalling starless cores. This poster focuses on the infall speed in particular.

The first analytic model, the two-layer model (Myers et al. 1996), is produced by assuming two layers of molecular gas along the line of sight with constant excitation temperature are approaching each other with a velocity $2v_{\text{in}}$. The expressions governing the emission profile ($\Delta T_{\text{B}}(v)$) of this model are

$$\Delta T_{\text{B}}(v) = J(T_f) [1 - e^{-\tau_f(v)}] + J(T_r) [1 - e^{-\tau_r(v)}] e^{-\tau_f(v)} - J(T_b) [1 - e^{-\tau_r(v) - \tau_f(v)}],$$

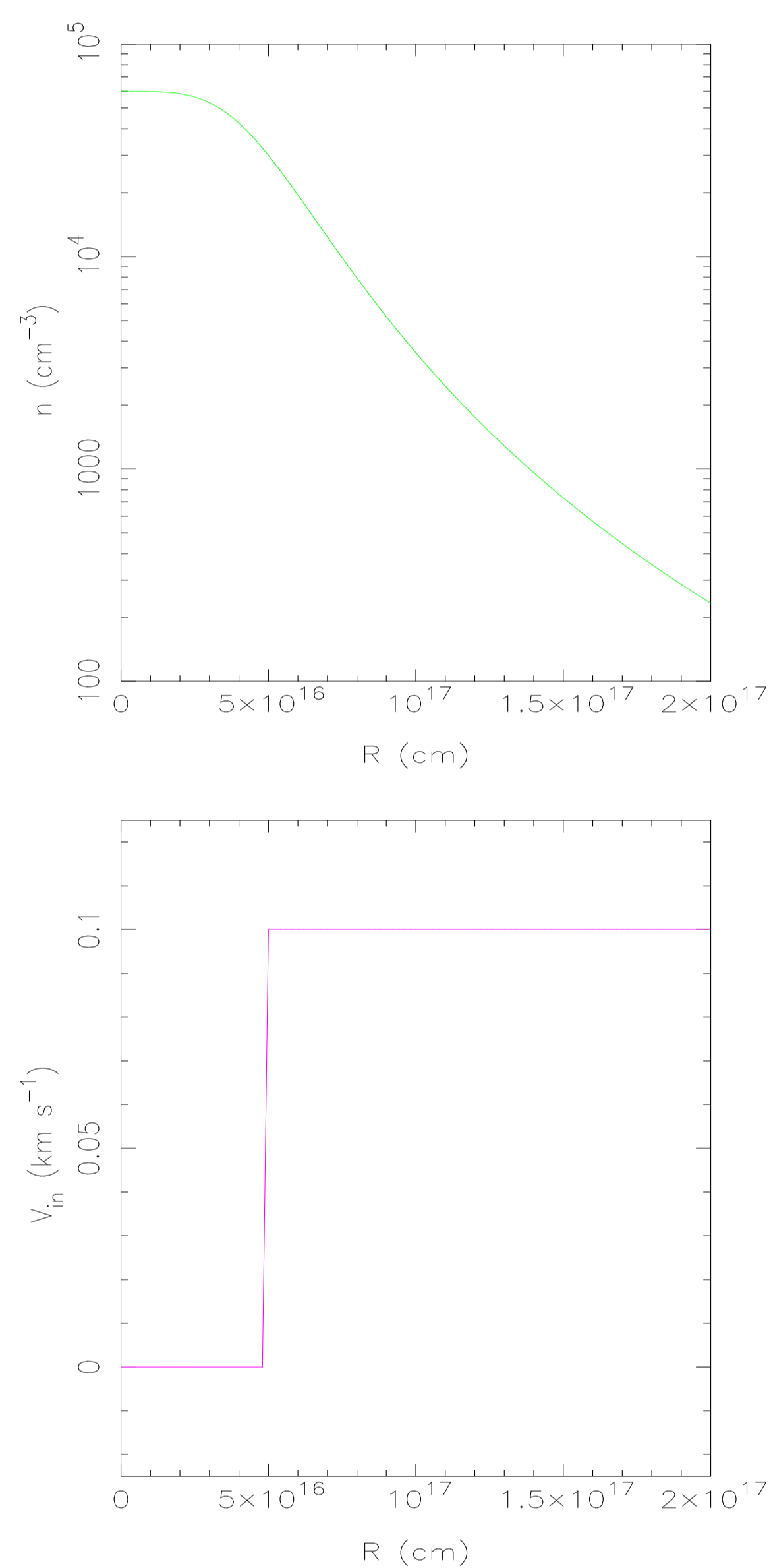
where τ_f and τ_r are the optical depths of the front and rear layers as a gaussian function of velocity centered on $v_{\text{LSR}} \pm v_{\text{in}}$, v_{LSR} is the LSR velocity, v_{in} is the infall speed, σ is the velocity dispersion, T_f is the excitation temperature of the front layer, T_r is the excitation temperature of the rear layer, and T_b is the background temperature.

The second analytic model, the hill model, assumes a static layer of molecular gas with a peak excitation temperature at the center, falling off linearly to the excitation temperature of two surrounding layers of constant excitation temperature and uniform infall speed along the line of sight. The expressions governing the emission profile of this model are

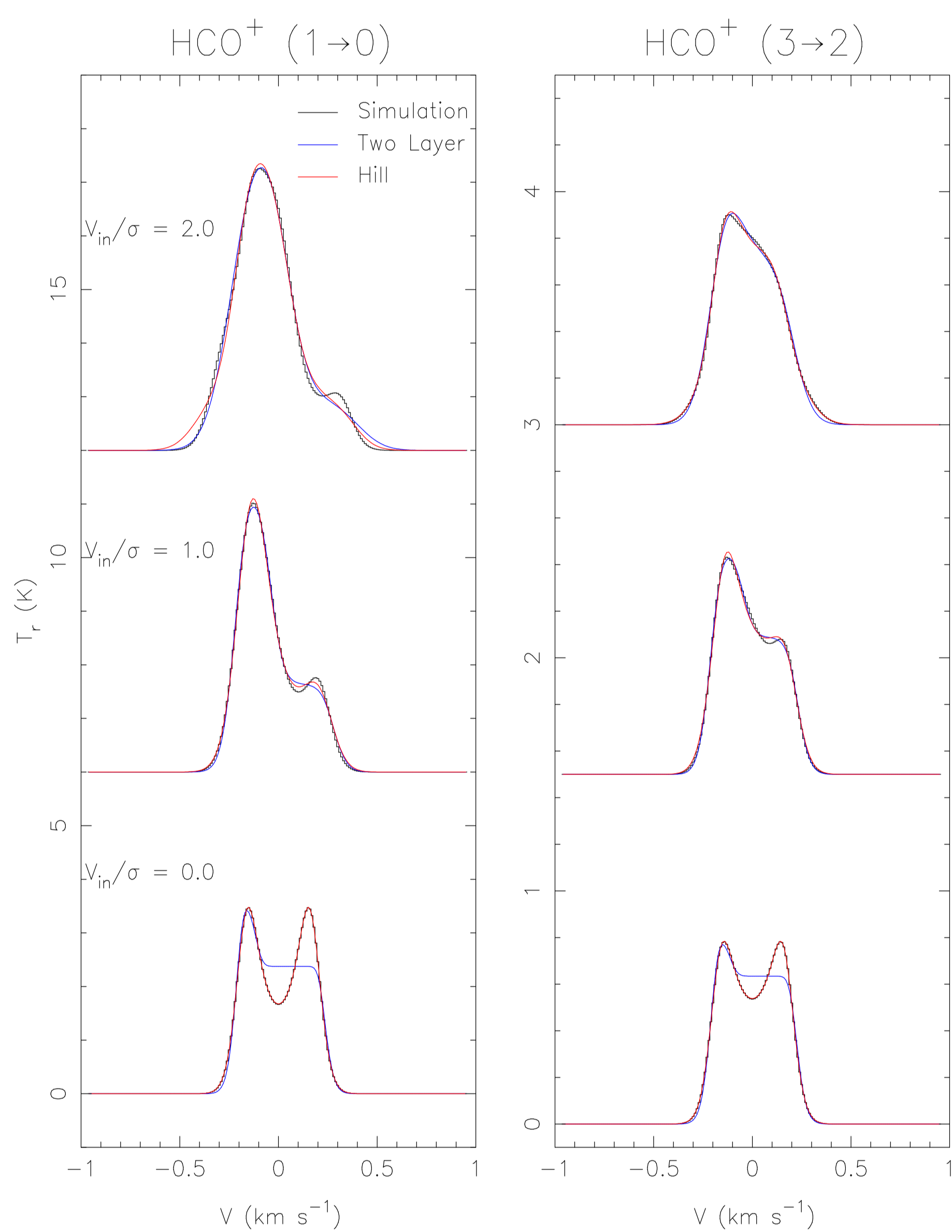
$$\Delta T_{\text{B}}(v) = (J(T_0) - J(T_b)) [1 - e^{-\tau_c(v) - 2\tau_F(v) - \tau_R(v)}] + (J(T_P) - J(T_0)) (1 - 2e^{-\tau_c(v)} + e^{-2\tau_c(v)}) e^{-\tau_F(v) / \tau_c(v)},$$

where τ_c is the optical depth of the central layers as a gaussian function of velocity centered on v_{LSR} , τ_F and τ_R are the optical depths of the front and rear layers of the envelope as a gaussian function of velocity centered on $v_{\text{LSR}} \pm v_{\text{in}}$, T_0 is the excitation temperature of the envelope, and T_P is the peak excitation temperature of the central gas layer. A more detailed treatment will be given in a future publication.

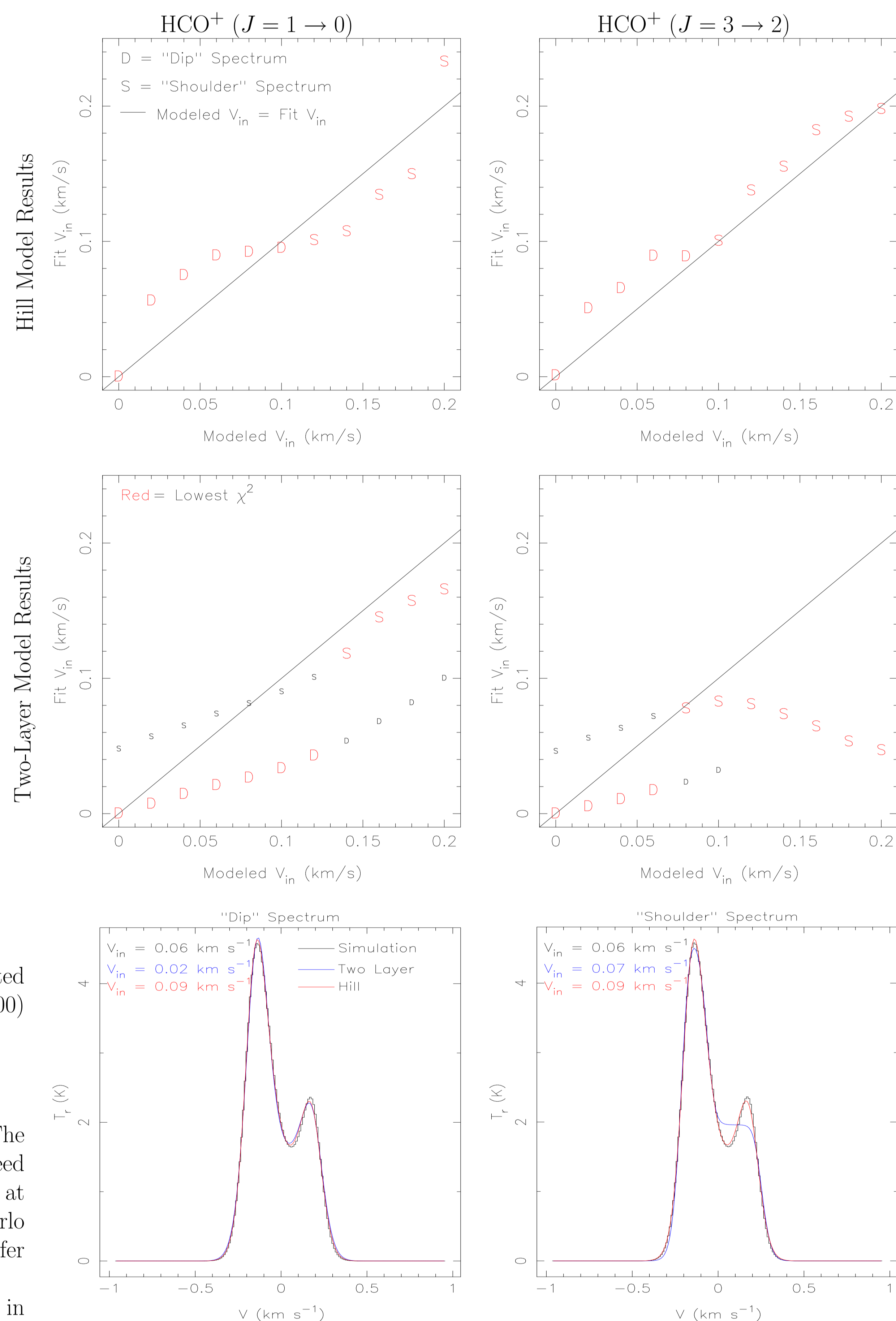
INPUT PROPERTIES



SAMPLE PROFILES



ACCURACY OF FITS



Fitting Model Cloud Emission

Above we present the results of fitting both the two-layer and hill analytic radiative transfer models to a simulated spherically symmetric infalling cloud whose emission has been calculated using the Hogerheijde & van der Tak (2000) Monte Carlo radiative transfer code. Our model cloud has a molecular hydrogen density given by the expression

$$n \propto \frac{1}{1 + (r/r_0)^\alpha},$$

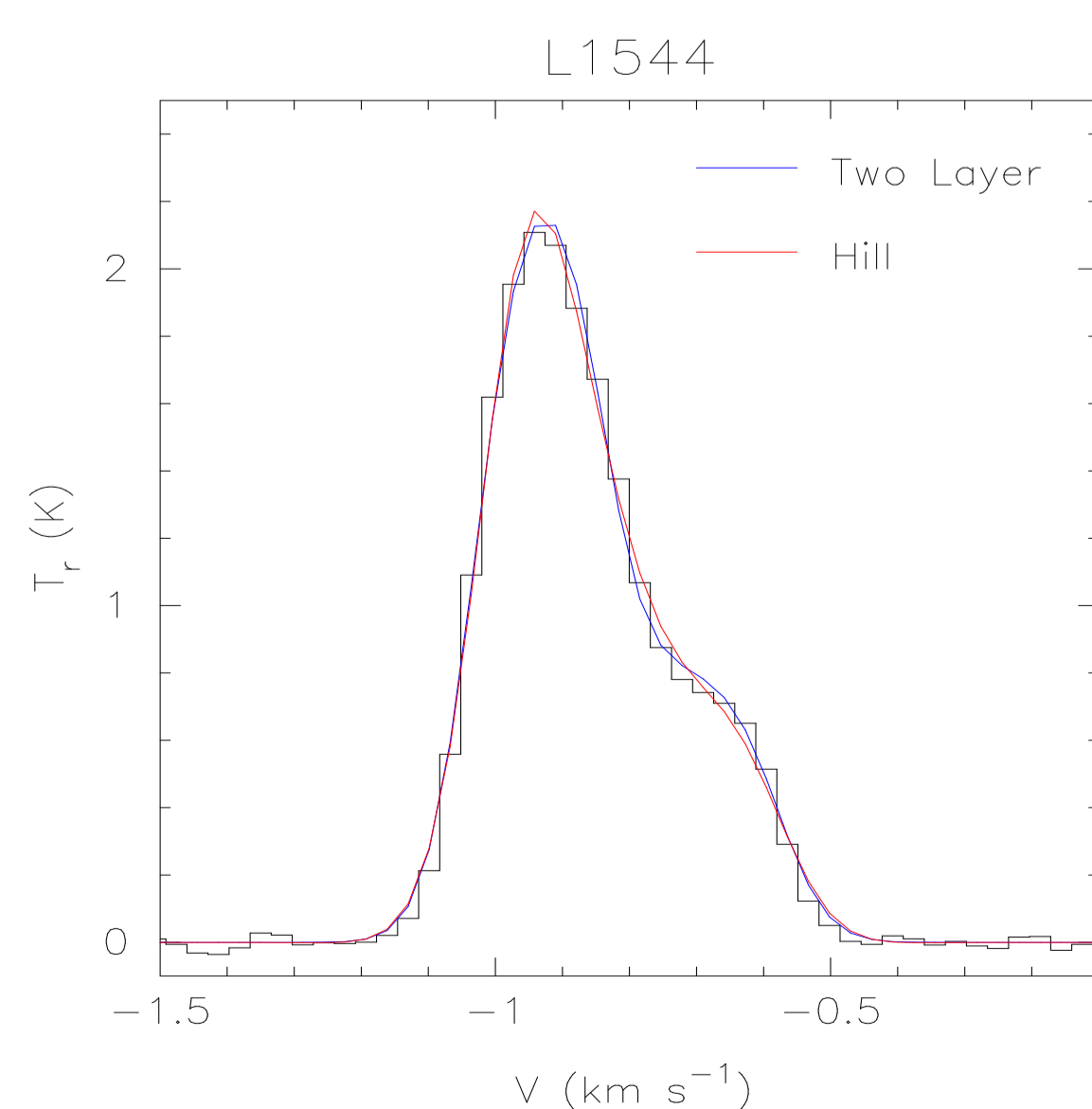
where α is 4.0 and r_0 is 5×10^{16} cm (Tafalla et al. 2002). This yields the density profile shown above on the left. The radial velocity of the cloud is 0 for $r < r_0$ and constant for $r > r_0$ as shown in the figure above. We vary the infall speed between 0 and 0.2 km s^{-1} . We hold the velocity dispersion constant at 0.1 km s^{-1} , and the HCO^+ relative abundance at 2×10^{-9} . Sample HCO^+ ($J = 1 \rightarrow 0$) and ($J = 3 \rightarrow 2$) spectra for several infall speeds derived from the Monte Carlo radiative transfer simulation are shown in black above. A corresponding fit by the two layer analytic radiative transfer model is shown in blue, and the fit by the hill analytic radiative transfer model is shown in red.

How well each analytic radiative transfer model reproduces the actual infall speed of the model cloud is shown in the above right. The hill model tends to match in infall speed within 0.04 km s^{-1} with an RMS of 0.026 km s^{-1} for a range of infall speeds from 0 to twice the velocity dispersion and does so uniquely. The two-layer model generally has two solutions within 0.07 km s^{-1} of the infall speed and tends to provide a good infall estimate when the infall speed is less than the velocity dispersion. Often the “shoulder” solution of the two-layer model provides a better estimate of the infall speed even when it has a higher χ^2 than the “dip” solution. Both methods also provide good estimates of the velocity dispersion.

Real Data: L1544

To the right we present the isolated hyperfine feature of the N_2H^+ ($J = 1 \rightarrow 0$) transition, observed in L1544 by Bourke et al. (in prep), shown in black. We also show our best fit hill and two-layer analytic radiative transfer models in red and blue respectively. Bourke et al. (in prep) have modeled several observed transitions in this source, many of which show an infall signature, and have derived an infall speed of 0.1 km s^{-1} based on simultaneous fitting of several transitions using a full 1-D Monte Carlo radiative transfer code. In the table below we present our best fits to the infall speed and velocity dispersion, which are quite close to the Monte Carlo value.

Model	V_{in} (km s^{-1})	σ (km s^{-1})
Two-Layer	0.095	0.083
Hill	0.134	0.108
Monte Carlo	0.1	0.085



References

- Bourke et al. in prep.
Hogerheijde, M. R., & van der Tak, F. F. S. 2000, A&A, 362, 697
Myers, P. C., Mardones, D., Tafalla, M., Williams, J. P., & Wilner, D. J. 1996, ApJ, 465, L133
Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815

“Dip” and “Shoulder” Spectra

In this investigation we have identified two characteristic line profile shapes which arise from the analytic models. The first is the “dip” spectrum which has two emission peaks separated by a dip. The second is the “shoulder” spectrum, which has a single emission peak and one flat or slowly descending asymmetric shoulder on the redshifted side of that peak. An example is shown in the two-layer fits (the blue line) of the two spectra above.

Typically the hill model makes a smooth transition from a “dip” to a “shoulder” spectrum as the line profile we attempt to fit moves from having a “dip” to having a “shoulder.” The two-layer model typically has a local χ^2 minimum at both a “dip” and “shoulder” solution, and sometimes even though the “dip” solution is a better fit, the “shoulder” solution yields a more realistic infall speed, as in the example above.

Conclusion

The two-layer and hill analytic radiative transfer models provide quick and fairly accurate estimates of the infall speed and velocity dispersion of centrally condensed infalling molecular clouds from their self absorbed line profiles. These models can be useful guides to understanding cloud motions and can provide input to more detailed models.

Acknowledgments

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