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High-excitation molecular lines from circumstellar disks

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Abstract. Observations of submillimeter lines of CO, HCO^+, HCN and their isotopes from circumstellar disks around low-mass pre-main sequence stars can be used to set constraints on the temperature and density distributions in these disks. The lines considered here originate from levels with higher excitation temperatures and critical densities than studied before (CO 6–5, HCO^+ and HCN 4–3), and are combined with interferometer data on lower excitation lines. We discuss the results for two disks, i.e., those around LkCa 15 and TW Hya. We find that the TW Hya disk has a warm surface layer and agrees well with a flaring disk geometry, while the LkCa 15 disk is cooler and can be described by either dust-settling in a flared disk or a flatter disk overall. The densities are well described by disk models in the literature.

1. Introduction

Protoplanetary disks are thought to be the predecessors of planetary systems. So far, the physical structure of these disks has been probed mostly by fitting the observed Spectral Energy Distribution (SED), thereby constraining the dust temperature and density profiles. This method is based on the changing dust-opacity at different frequencies: at the high opacities at short wavelengths, the temperature in the upper layer is probed whereas at the low opacities at longer wavelengths the total disk-mass is measured. One of the mayor results from this analysis is the recognition that disks have a flared geometry (Kenyon & Hartmann 1987), where the surface layer is heated by the stellar light and the interstellar radiation field. The fit to the SED does not, however, give a unique solution. A second method to determine the density and temperature distribution is by modeling molecular line emission. With the currently available spatial resolution and calibration accuracies, this again gives a non-unique result, but the combination of both techniques should give stricter constraints. In this work we use observations presented in Kastner et al. (1997), Qi (2000) and van Zadelhoff et al. (2001) to probe the densities and temperatures in two disks around pre-main sequence stars and test different disk models in the literature.

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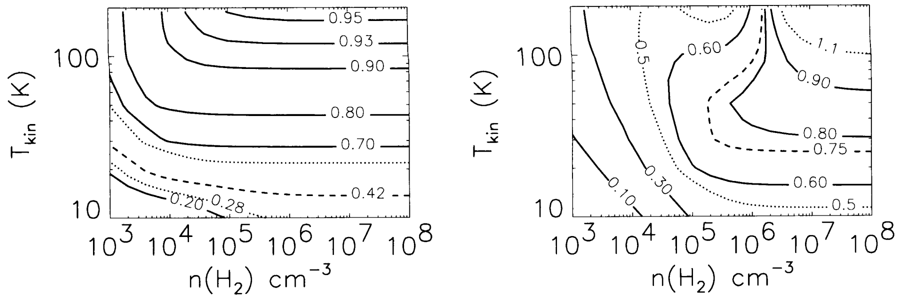

Figure 1. Left: CO 6–5/3–2 ratio; Right the HCO^+ 4–3/1–0 ratio. Both figures show the observed ratio (dashed lines) for the source LkCa 15. Dotted lines shows the upper and lower limits assuming an observational error of 20%. The CO and HCO^+ column densities have been chosen such that the lines are optically thick.

2. Observations

Spectral line observations were taken for several pre-main sequence stars, including LkCa 15 and TW Hya. The *James Clerk Maxwell Telescope* (JCMT) was used to obtain high rotational lines of CO, HCO^+ and HCN and their main isotopomers. These data were complemented by CO 6–5 observations using the *Caltech Submillimeter Observatory* (CSO). Interferometer maps of the lower rotational lines have been obtained by Qi(2000) using the *Owens Valley Radio Observatory* (OVRO).

3. Interpretation

The observed line ratios give rough estimates of the physical structure in the line emitting regions adopting a simple constant density and temperature model. Subsequent more thorough modeling can distinguish between different disk models (van Zadelhoff et al. 2001). The calculations presented here use a one-dimensional escape probability analysis where the integrated intensity of two lines is calculated for different temperatures and densities (Jansen et al. 1996). The temperature can be estimated using the CO lines, while the density is better probed by large dipole molecules like HCO^+ and HCN. The isotopomers can be used for determining both the physical parameters and the optical thickness of the lines. In Figure 1, the CO 6–5/3–2 ratio and the HCO^+ 4–3/1–0 are shown. From the isotopic ratios, it is found that the lines from the main isotopes are severely optically thick: $^{12}CO/^{13}CO$ 3-2 = 3.3 (LkCa 15) and 7.6 (TW Hya), compared with the normal ratio of $[^{12}C]/[^{13}C]$=60. For both CO and HCO^+, the ^{13}C isotopomers are moderately thick as deduced from the $^{13}C/^{18}O$ isotopic variants. HCN and $H^{13}CN$ are both extremely optically thick, since the ratio of the $HCN/H^{13}CN$ 1_2–0_1 lines is $\approx$1. Thus, the emission from the main isotopes arises from the upper layers of the disk, whereas that from the less abundant species probes deeper into the disk.

From the CO 6–5/3–2 ratio, a large part of the emitting gas for LkCa 15 is found to be at $T \approx 15 - 30$ K, similar to the range indicated by the ^{13}CO

3–2/1–0 ratio. TW Hya seems to be warmer with at least ~ 40 K based on the CO 6–5/3–2 limit and the CO 4–3 (from Kastner et al.)/3–2 ratio. The density in the LkCa 15 disk derived from the HCO^+ 4–3/1–0 ratio is $> 2 \cdot 10^5$ cm^{-3} while the $H^{13}CO^+$ 4–3/1–0 ratio gives $< 10^7$ cm^{-3}. HCN in LkCa 15 probes even higher densities, ranging from 10^7 up to 10^8 cm^{-3}. For TW Hya, the HCN 4–3/3–2 ratio from Kastner et al. probes densities in the same range up to 10^7 cm^{-3}.

4. Conclusion

The simple one-dimensional analysis indicates that the surface layer of the TW Hya disk has a temperature of at least 40 K, suggesting that the surface layer is heated by stellar radiation and X-rays as well as the ambient interstellar field. This would be most effective if the disk has a flared geometry. For LkCa 15, the temperature of 15–30 K does not require much extra heating. The inferred densities are consistent with values expected for the intermediate layers of disks where CO has not yet frozen out. More detailed 2-D radiative transfer modelling by van Zadelhoff et al. (2001) shows that the line ratios are well fitted by gaussian density distributions in the vertical direction such as in models by Chiang & Goldreich (1997) and Bell (1999), or density distributions calculated in hydrostatic equilibrium such as presented by D'Alessio et al. (1999).

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