EVIDENCE FOR THE EVOLUTION OF GRAIN PROPERTIES IN THE NGC 2024 STAR FORMING RIDGE

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ABSTRACT. High-resolution images of the NGC 2024 molecular ridge in CS(2–1) and 3 mm continuum emission have been obtained using the Owens Valley millimeter array. The data are used to determine the temperature and dynamics of the ridge, and to ascertain the evolutionary state of the embedded protostars FIR2–7. Dust continuum emission is detected from all six FIR sources. The CS(2–1) follows the ridge closely, but does not always coincide with the FIR sources. Direct comparison of column density estimates derived from the CS and the dust emission in the ridge shows that for all FIR sources except FIR5 both methods are in agreement to within a factor of two, assuming a dust opacity $\kappa_{3\mathrm{mm}} = 0.01\ \mathrm{cm}^2\ \mathrm{g}^{-1}$. However, away from the FIR sources strong CS(1–0) emission is observed in several compact clumps which, with the above dust opacity, should have been detected in 3 mm dust continuum. The brightness temperature of the CS, ~ 40 K, rules out the possibility that the high line-to-continuum ratio is due to low gas temperatures; the discrepancy can be resolved if $\kappa_{3\mathrm{mm}}$ is a factor of 10 lower away from the FIR sources. A new high-resolution image of the 450-μm dust continuum emission obtained using the James Clerk Maxwell Telescope supports this hypothesis. These results suggest an evolution in the physical properties of the dust grains, possibly grain size, between quiescent regions in the ridge and the sites of active star formation.

1. INTRODUCTION

When written in the usual long-wavelength form, the dust opacity $\kappa_\nu = \kappa_0(\nu/\nu_0)^\beta$ is observed to have β in the range 0 to 1 in T Tauri disks rather than the theoretical limit for small grains of $\beta = 2$ (Beckwith & Sargent 1991; Mannings & Emerson 1994). This has been interpreted as an evolution of the dust properties, perhaps an increase in grain size, in T Tauri disks compared to the interstellar medium. To ascertain whether the change in β occurs only during the later phases of T Tauri disk evolution, or whether similarly low values for β are observed in the high-density circumstellar material of more embedded sources, we have studied the NGC 2024 star forming ridge in both dust emission and molecular line emission. The FIR sources in the NGC 2024 cloud were identified through their mm continuum emission by Mezger *et al.* (1988, 1992). Three of the sources, FIR4, FIR5 and FIR6 are associated with molecular outflow, and so contain embedded protostars (Chandler & Carlstrom 1996; Richer *et al.* 1989; Richer 1990). The other FIR sources may be younger, even pre-protostellar.

2. OBSERVATIONS

Using the Owens Valley mm array three fields covering FIR2–7 in the NGC 2024 ridge were observed in 98 GHz continuum and CS(2–1) emission, with a synthesized beam $\theta_b = 4.5 \times 3.6''$ (1900 $\times$ 1500 AU). Also presented is an image of the 450-μm dust continuum obtained using the 15-m James Clerk Maxwell Telescope, with $\theta_b = 8''$ (3300 AU).

3. CONTINUUM EMISSION

We detect 3-mm continuum emission from all the FIR sources covered by our observations (Figure 1a). Ridges of free-free emission oriented east-west are also detected, and are locations where the foreground HII region is ionization-bounded by the molecular cloud (Gaume *et al.* 1992). The spectral indices of all the FIR sources except FIR4 are consistent with dust emission (Chandler & Carlstrom 1996). At FIR4 a flatter spectral component is also needed, which may be due to confusion with the nearby ridge of ionized gas.

4. CS AND DUST AS TRACERS OF $N(H_2)$

The CS(2–1) is represented as a greyscale in Figure 1b. By making some assumptions about the temperature, the CS abundance, and the dust opacity, both the dust and the integrated CS(2–1) emission can be used to estimate the column density of molecular hydrogen in the ridge. For the dust we use $T_{\rm d} = 30$ K, $\kappa_0 = 0.1$ cm^2 g^{-1} at $\nu_0 = 10^{12}$ Hz (*cf.* Hildebrand 1983; Beckwith *et al.* 1990), and $\beta = 1$, *i.e.*, the value commonly observed in T Tauri disks rather than the interstellar medium. For the CS we use an abundance relative to molecular hydrogen of 2.5×10^{-9} (as found for the Orion ridge: Blake *et al.* 1987), $T_{\rm ex} = 40$ K, and $\tau_{21} = 1$. We find good correspondence (within a factor of 2) between the column densities derived using both methods at all the FIR sources apart from FIR5. However, there is a striking anti-correlation between the CS and the dust at FIR5 and in the CS condensations to the east of FIR5/6.

5. CS/DUST DISCREPANCIES AT FIR5/6

Close to FIR6, spectra of the CS(2–1) emission are dominated by the compact molecular outflow from that source (see Chandler & Carlstrom 1996). The condensations close to FIR5, however, appear to be quiescent, with Gaussian line profiles and no sign of star formation. At these locations there is a serious discrepancy between the

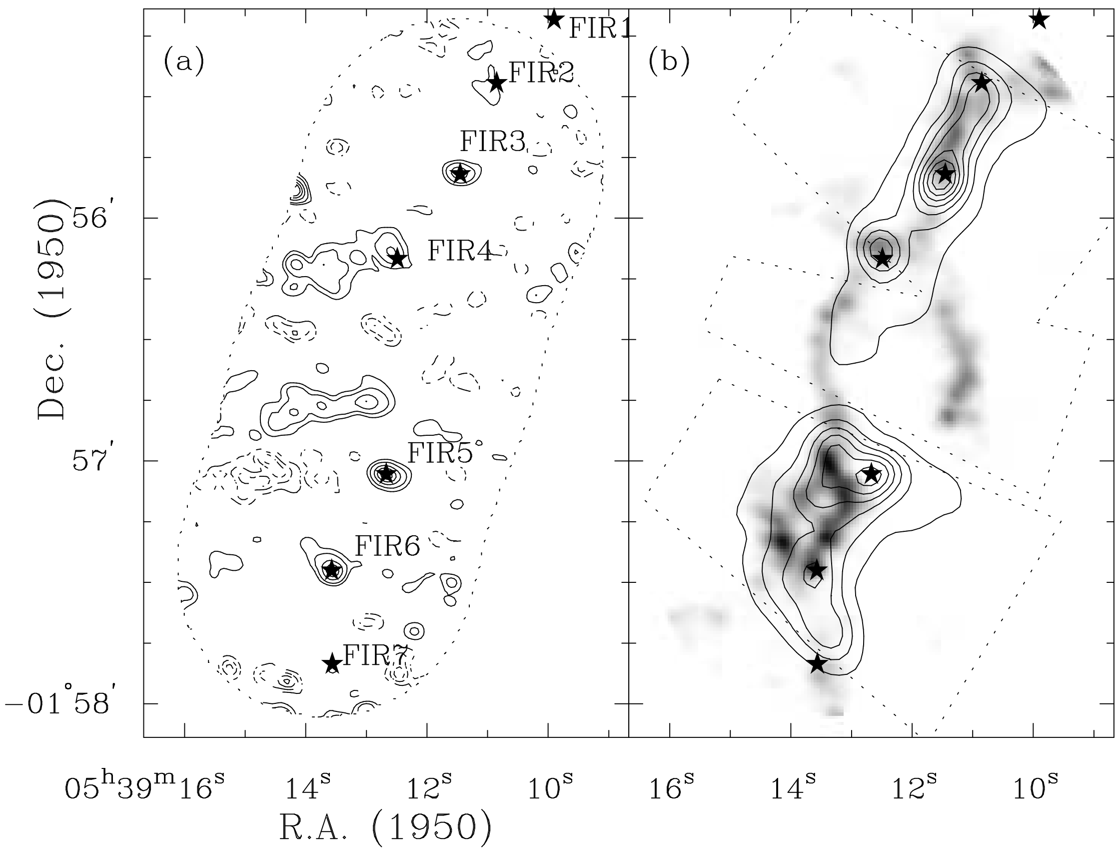

Figure 1. (a) 3-mm continuum image of NGC 2024. Stars indicate the positions of FIR1–7. The outline gives the 50% response level of the region imaged. (b) contours of the 450-μm continuum emission overlaid on a greyscale of integrated CS(2–1) emission. The outline gives the area of the 450-μm map.

column density derived from CS compared to the dust. The most plausible explanations for the discrepancies both at FIR5, where $N(\mathrm{H_2})_{\mathrm{dust}}/N(\mathrm{H_2})_{\mathrm{CS}} \sim 10$, and in the CS condensations, where $N(\mathrm{H_2})_{\mathrm{dust}}/N(\mathrm{H_2})_{\mathrm{CS}} \sim 0.15$, are given below.

FIR5: Since $\tau_{\mathrm{CS(2-1)}} \propto N(\mathrm{H_2})/T_{\mathrm{ex}}^2$ while $\tau_{\mathrm{dust}} \propto N(\mathrm{H_2})$, an increase in the temperature of the gas and dust to $T \gtrsim 100$ K can resolve the discrepancy without invoking depletion of CS or anomalous dust properties. A dust temperature of 100 K leads to a source luminosity of 700 $\mathrm{L_\odot}$. However, because no high-resolution 50–100 μm measurements of FIR5 exist, there is no good constraint on the dust temperature in this source. It is therefore also possible that the depletion of CS in low temperature, high density gas at FIR5, can explain our observations.

CS condensations: The brightness temperature of the CS lines is $T_{\mathrm{b}} \approx 40$ K, and so should have been detected in continuum emission if the dust properties were the same as those in the FIR sources. κ_{3mm} must therefore be lower in the CS condensations than in the FIR sources, either due to a decrease in κ_0 or an increase in β. Below we show that the latter is most likely to be the case.

6. β IN THE CS CONDENSATIONS AND FIR SOURCES

In Figure 1b we overlay the 450-μm continuum emission from the ridge on the integrated CS(2–1). At this shorter wavelength strong dust emission is also associated with the CS condensations, showing that the spectral index at those locations is considerably steeper than in the FIR sources. To estimate the value of β we have subtracted the extended emission from the 450-μm map and compared it with the 3-mm continuum. After applying a Rayleigh-Jeans correction and an opacity correction to the 450-μm data we find for the protostars FIR5 and FIR6 a value for β of 1.2 ± 0.2 and 0.9 ± 0.2 respectively. At the CS condensation east of FIR5 on the other hand we obtain $\beta > 1.7$. For FIR3, which is younger than FIR5 and FIR6, $\beta = 1.6 \pm 0.2$. Thus a variation of β with protostellar age is suggested, even in these very early phases of star formation. It is possible that this evolution of β corresponds to an increase in grain size in dense interstellar environments.

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