Physical and Chemical Evolution of Dense Cores from Isotopic CO, HCO^+, NH_3, and HC_3N Observations

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The Complex

The Cocoon Nebula complex in Cygnus includes the optical star cluster IC 5146 (whose most massive stars are early-B) and the spatially coincident HII region S125 (Sharpless 1959; Blitz, Fich & Stark 1982), which lies at one end of an otherwise dark collection of associated molecular clouds, L1010–55 (Lynds 1962) — see Figure 1. This structure of a prominent cluster at the end of an elongated quiescent dark cloud is similar to that of the complexes in Orion A, Ophiuchus, and Corona Australis. The Cocoon presents a unique opportunity to study the effects of star formation on dense cores and vice versa, since it is lies in a relatively unconfused area of the sky and there seem to be examples of cores currently in different stages of star formation as well as those that seem to be quiescent. Thus an analysis of this complex could contain lessons on what the preconditions necessary for star formation to take place are, and what effects the star formation that results has on the parent core material.

Observations

The complex comprising IC 5146 and associated dark clouds was studied with a variety of molecular line tracers in order to investigate the properties of the dense cores. Complete maps were made with the 15-element QUARRY receiver at the FCRAO 14m telescope in the J=1→0 lines of $C^{18}O$ and HCO^+ — see Figure 2. These are at higher resolution than the large-scale surveys previously published (CO, Dobashi *et al*. 1992; and ^{13}CO, $C^{18}O$, & CS, Lada *et al*. 1994) and, while being consistent given the different beamsizes, reveal much more structural information than the earlier maps.

At the various peaks of emission, we also surveyed eight different dense gas tracers at the NRAO 12m and Haystack 37m telescopes in order to investigate the physical properties of the cores. The species surveyed are ^{13}CO, $C^{18}O$, HCO^+, $H^{13}CO^+$, DCO^+, & HCO (NRAO), and NH_3 & HC_3N (Haystack).

Results

From the ^{13}CO and $C^{18}O$ data, we derive optical depths and excitation temperatures assuming an intrinsic abundance ratio, and from these further derive column densities, volume densities, and masses, while the maps give the cores' sizes. Some of these quantities for each core are displayed in Figures 3–8. Note the clear distinction between the cores closely associated with the optical cluster and HII region (the "bright cores") and those removed from the cluster (the "dark cores"). This distinction is amplified when similar analyses are performed for the isotopic HCO^+ data, and also the Haystack data.

Summary

The star-forming complex comprising IC 5146 and associated dark clouds was studied with a variety of molecular line tracers in order to investigate the properties of the dense cores, and a number of systematic effects in the cores' evolution have been elucidated for the first time.

1) Cores closely associated with the optical cluster ("bright cores") are distinctly hotter and somewhat denser than cores removed from the cluster ("dark cores"). The dark cores also have a fairly uniform excitation temperature.

2) For both CO and HCO^+ isotopomers, where the excitation temperatures are high, the optical depths in these low-lying transitions are low, but the total CO column densities are comparable in

the different cores. Thus the main physical difference between the bright and dark cores is that the molecular populations have been excited to the higher J levels.
3) We find that the $C^{18}O$ column density correlates extremely well with IR extinction, that HCO^+ emission correlates well with star-forming activity, and NH_3 and HC_3N emission are brightest in the dark cores but are anticorrelated with each other.
4) Early-time chemical evolution models of dark cores predict a variation with time of the NH_3/HC_3N ratio, which we may be seeing for the first time.
5) The isotopic HCO^+ data also show that strong fractionation of deuterium has occurred in all the dark cores, and fractionation of ^{13}C in the outer parts of cores, similar to what has been observed in other clouds.
6) Previous work has also suggested that HCO is most abundant in the interface zones between molecular clouds and HII regions; HCO emission in IC 5146 is almost entirely confined to the bright cores and thus dramatically confirms this trend.

The ensemble of information from these tracers shows that the warmer bright cores exhibit distinctly different chemical and physical properties from the cooler dark cores, but that there are also differences among the dark cores. See the figure captions for more discussion.

References

Blitz, L., Fich, M., & Stark, A.A. 1982, *ApJS*, **49**, 183
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Lada, C.J., Lada, E.A., Clemens, D.P., & Bally, J. 1994, *ApJ*, **429**, 694
Lynds, B. 1962, *ApJS*, **7**, 1
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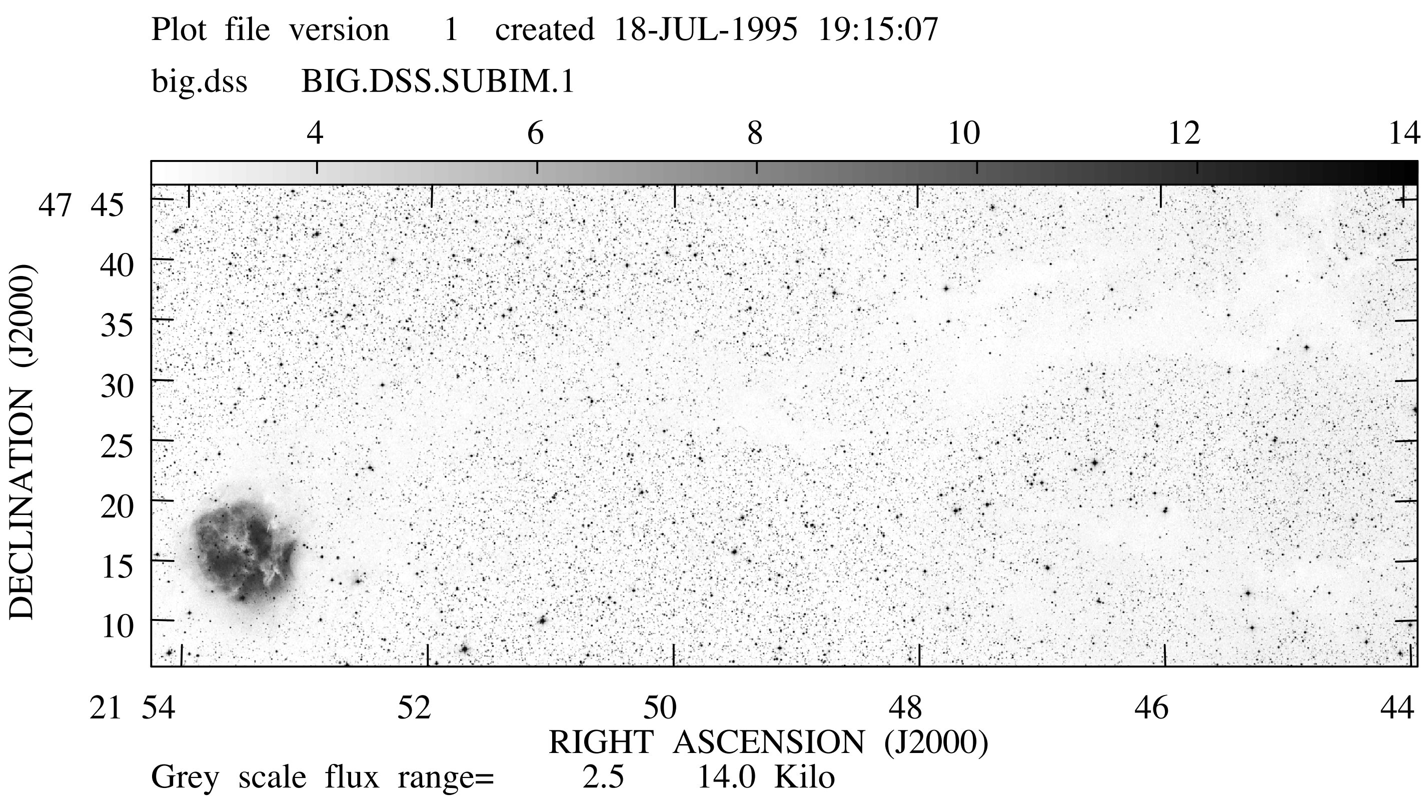

Figure 1. Digital Sky Survey image of the region. IC 5146/S125 is the cluster/HII region to the east, while the Lynds Dark Clouds 1010–1055 trail off to the west.

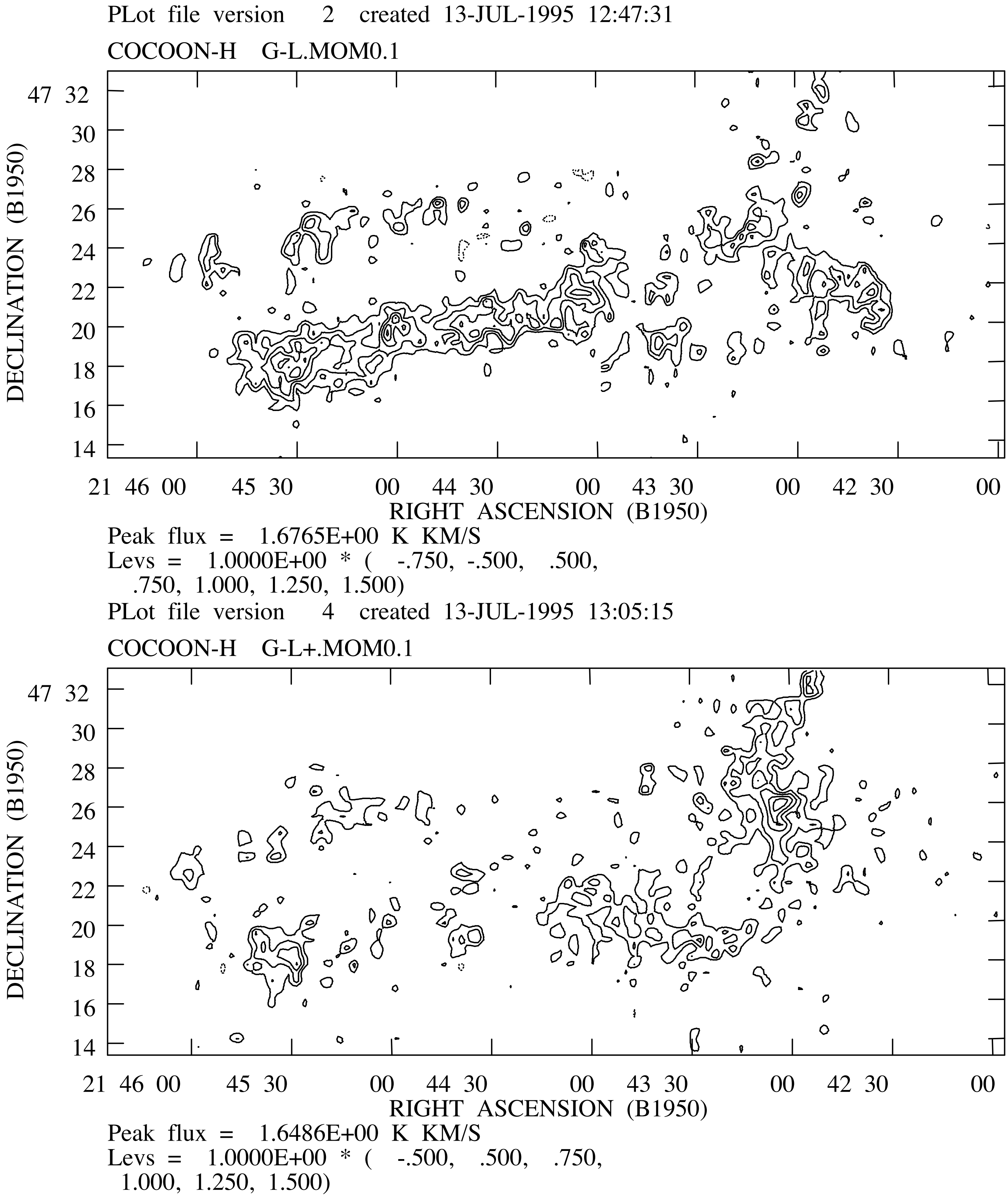

Figure 2. Comparative QUARRY maps of the 8pc-long dark filament to the west of IC 5146 in $C^{18}O$ (*top*) and HCO^+ (*bottom*). While the overall correspondence to the optical dust lane (Fig. 1) is good, the detailed emission structure in these two tracers is quite different. A colour overlay of these maps is also available from the authors.

Figures 3–7. (next page) Comparative brightness of various spectral lines at the survey positions. Note in many cases the clear distinction between cores near the optical cluster ("*bright cores*") and those far from the cluster ("*dark cores*"), e.g. in the filament.

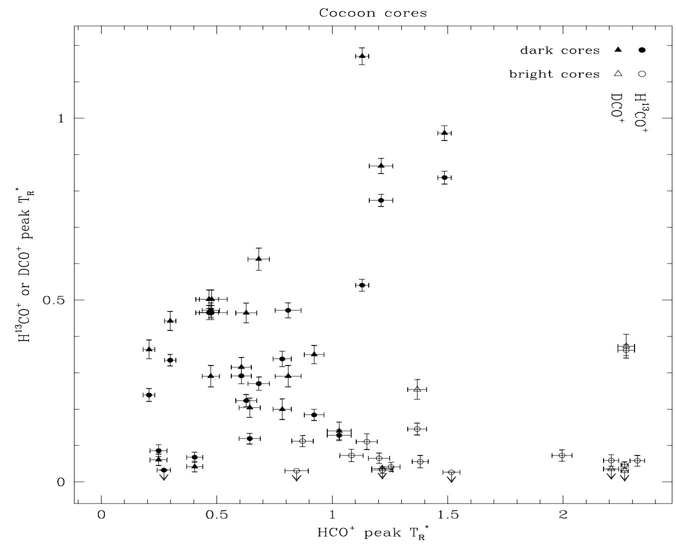

Figure 3. Here HCO^+ $1\rightarrow0$ is optically thick, so it measures T_{ex}. Its rarer isotopes are optically thin, and so measure τ. This figure shows that the cluster cores have a systematically higher T_{ex} and lower τ (in this line) than the dark cores, although the column densities are about the same (see Fig. 8).

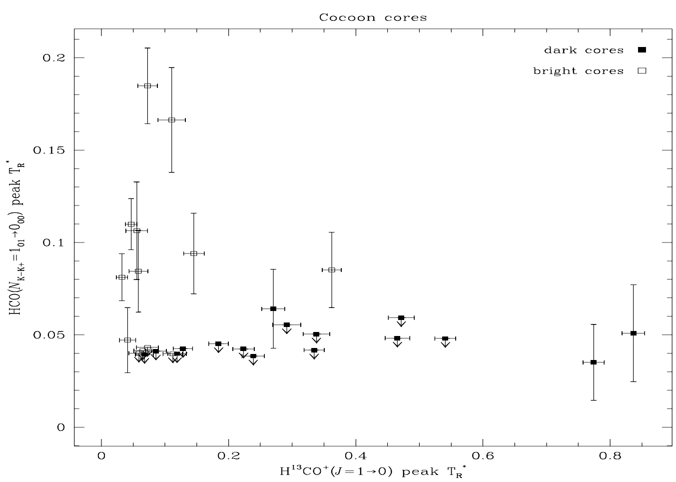

Figure 4. HCO traces PDRs, so comparing a cold gas tracer like $H^{13}CO^+$ reveals a *chemical* dichotomy between the warm & cold cores, besides the *physical* differences shown in Fig. 3.

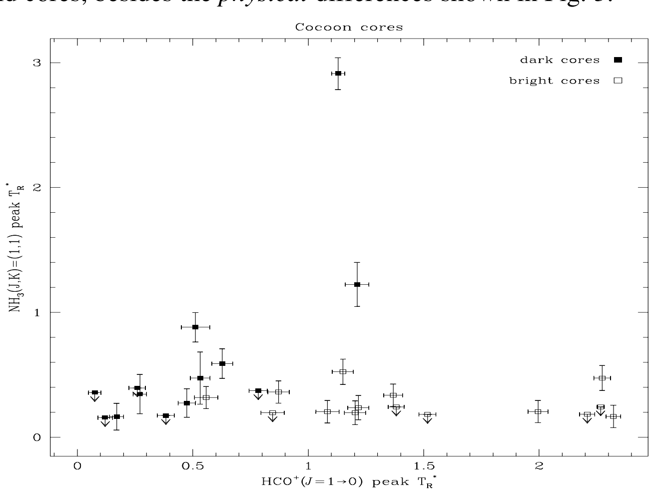

Figure 5. Further illustrating the different chemical states of warm vs. cold cores, compare HCO^+ & NH_3.

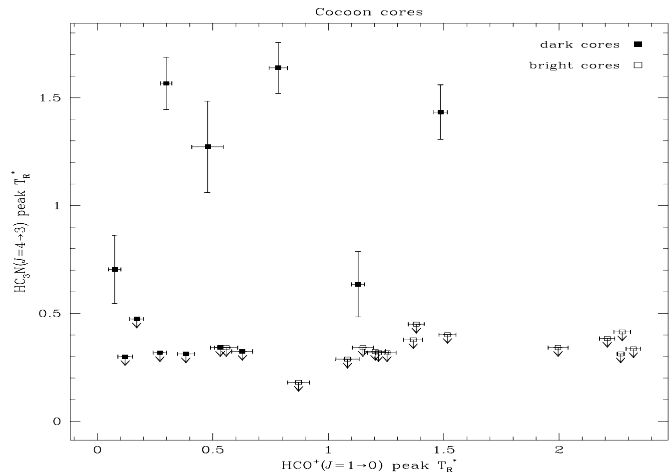

Figure 6. And compare HCO^+ with HC_3N.

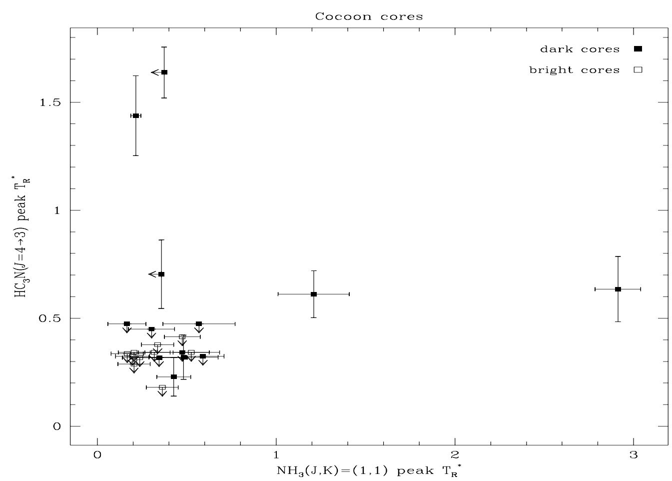

Figure 7. However, even cold gas tracers such as NH_3 and HC_3N do not necessarily show up in the same gas. The divergence shown here between these two tracers, in just the cold dark cores where they are detected, rivals that seen in Fig. 4!

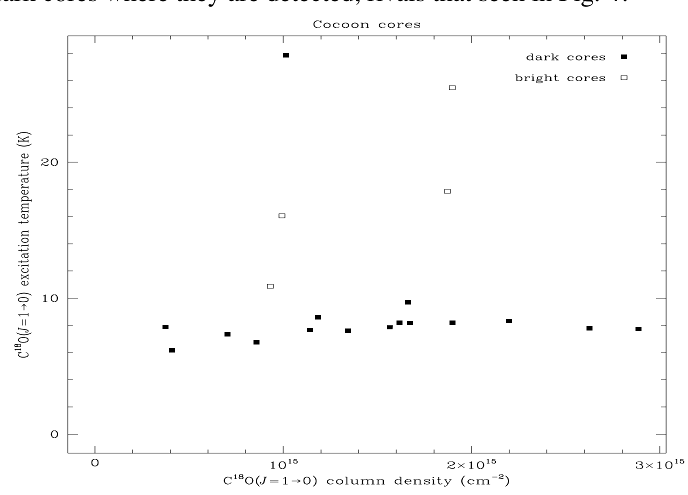

Figure 8. Physical analysis for ^{13}CO and $C^{18}O$ data assuming a constant abundance ratio. The cold, dark cores have a fairly uniform T_{ex}, but both warm and cold cores have similar column densities. This means that the small optical depths seen in the warm cores are due to their high excitation, pushing the level populations up the J-ladder without destroying the molecules, thus preserving their total abundance.