Tracing molecular cloud formation with [CI] and [CII]

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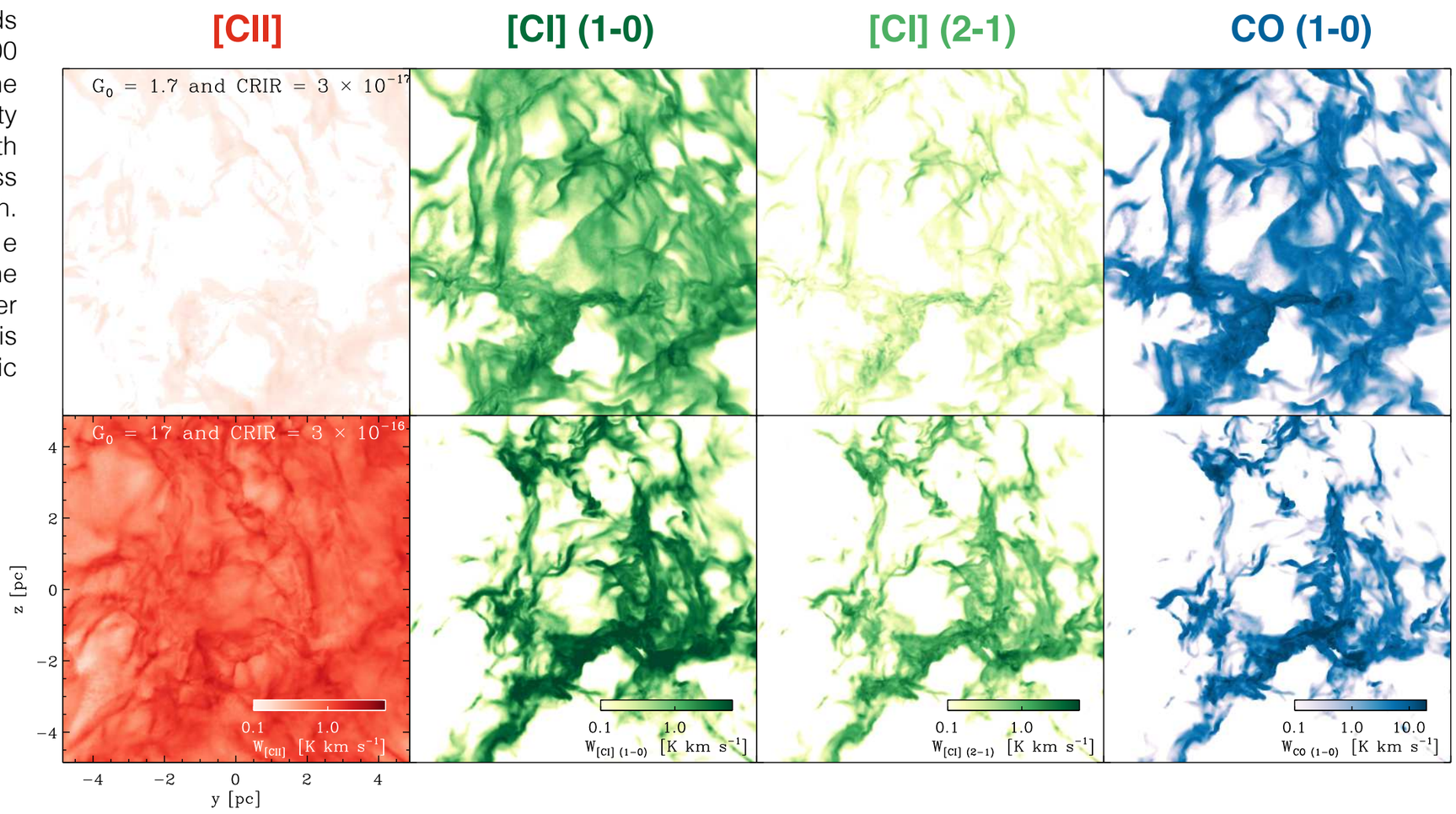
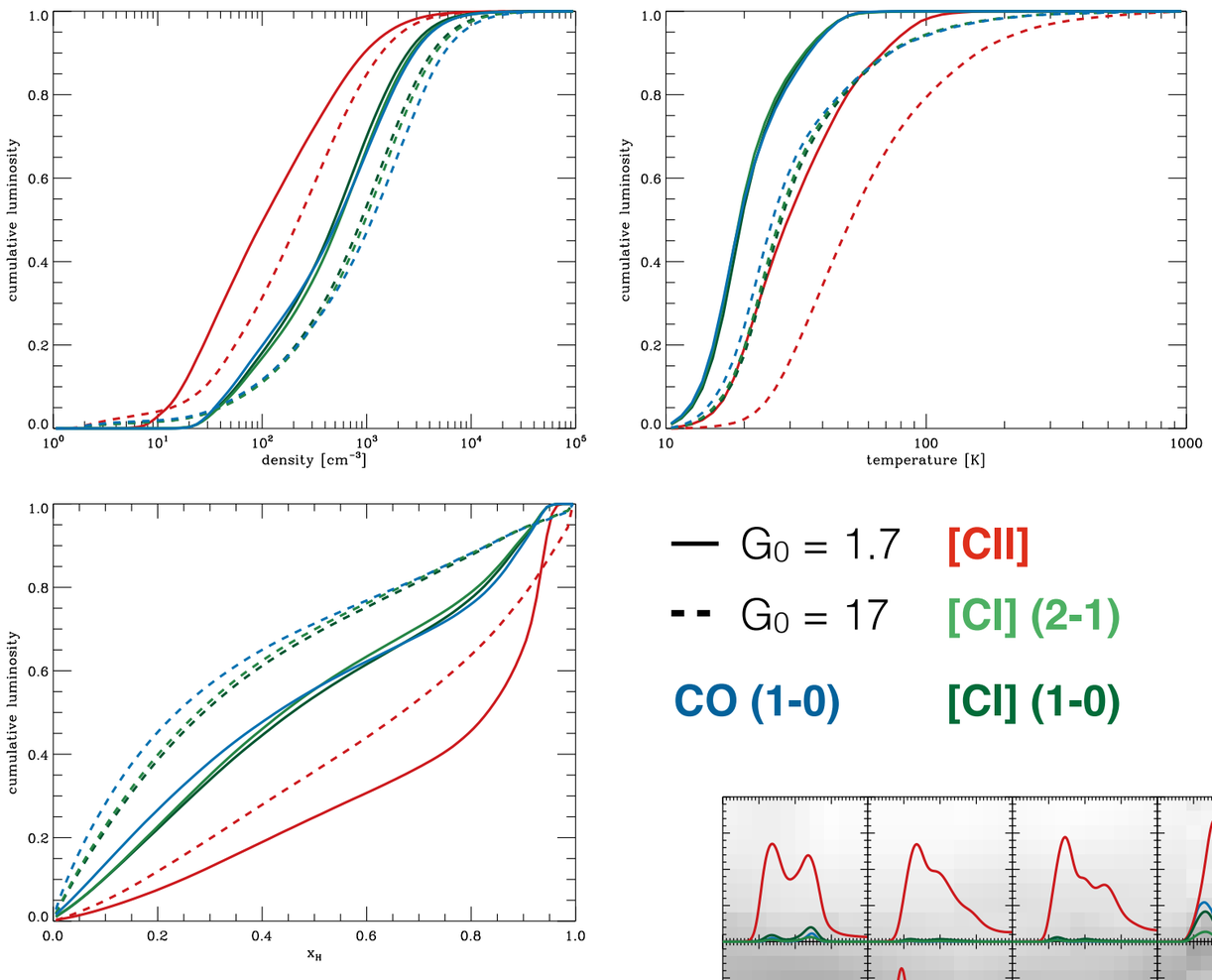
Cloud-Cloud Collisions

We present radiative transfer post-processing of a simulation of collisions between two clouds. The clouds have a mass of 10^4 $M_\odot$ and start at n = 10 cm^{-3} and 300 K. There is a uniform magnetic field of 3 μG along the collision axis, and the clouds are colliding with a velocity of 3.75 km/s each. The simulations are performed with the Arepo code (Springel 2010), with an initial cell mass of 0.005 $M_\odot$, and we enforce 32 cells per Jeans length. Our chemical/thermodynamic model follows the prescriptions outlined in Glover & Clark (2012), with the CO treated using the approximations in Nelson & Langer (1999). The radiative transfer post-processing (LVG) is performed with the RADMC-3D code, using the atomic and molecular data from the Leiden Lambda database.

Integrated Intensity Maps

The maps on the right show the integrated intensity of the [CII], [CI] (1-0) & (2-1), and CO(1-0) transitions in a region of the cloud just before the first star forms (at around 5 Myr into the simulation). The maps look normal to the plane of the collision (i.e. along the collision axis). The two rows show different environmental conditions: the top row has a UV field of G_0 = 1.7 and a cosmic ray ionisation rate (CRIR) of 3 × 10^{-17} s^{-1}, and the bottom row shows a simulation with 10 times these values. We see that the emission is strongly dependent on the level of UV and the CRIR.





Origin of Emission

The plots on the left show the cumulative emission as a function of physical conditions in the cloud. These plots are made by converting that 3D cubes of density, temperature and chemical abundance that are used in the RADMC-3D calculation, into the same position-position-velocity space that we use in emission cubes. We can then match spectral features with their physical origin. Note that the results in the these plots are approximate: a single grid cell has a unique velocity, while it will emit over a range of velocities due to thermal broadening of the line.

We see that the physical regime probed by [CI] is similar to that probed by CO, with 50% of the emission coming from above 400 cm-3 and below 20K, in gas that is mainly molecular in nature. In contrast [CII] probes the atomic, dense (~100 cm^{-3}) gas above 30K. Interestingly, we see that very little [CII] emission arises from the 'flows' that created the cloud, which had a density of 10 cm^{-3}, but rather from the denser, post-shock gas just before it turns molecular.

Again we see that the origin of the emission is dependent on the strength of the UV field and the value of the CRIR. As we increase the UV/CRIR, we see that the emission from the CO and the [CI] lines is more likely to come from more molecule rich gas (i.e. low x_H). This is simply because the carbon in the unshielded, and thus mainly atomic gas, is maintained in the form of C^+.

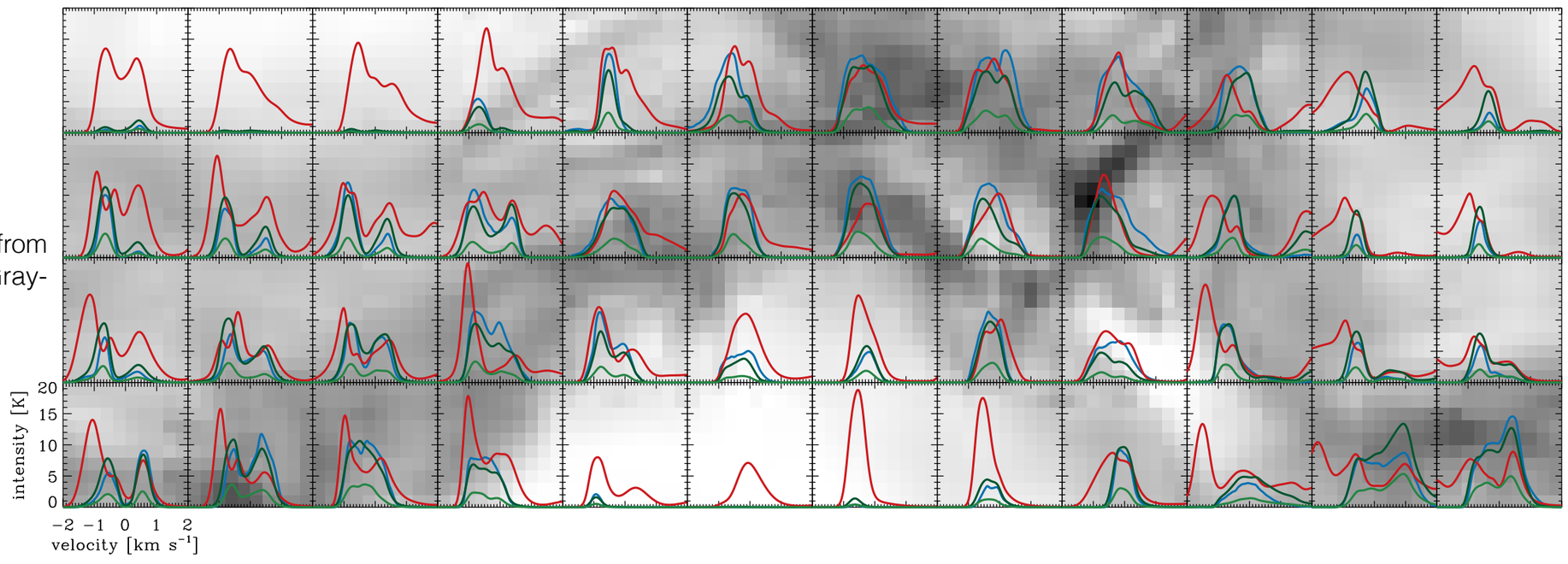
Multi-tracer Spectra

The image on the right shows the spectra from the bottom right ridge in the above maps. Gray-scale is column density. Line are as follows:

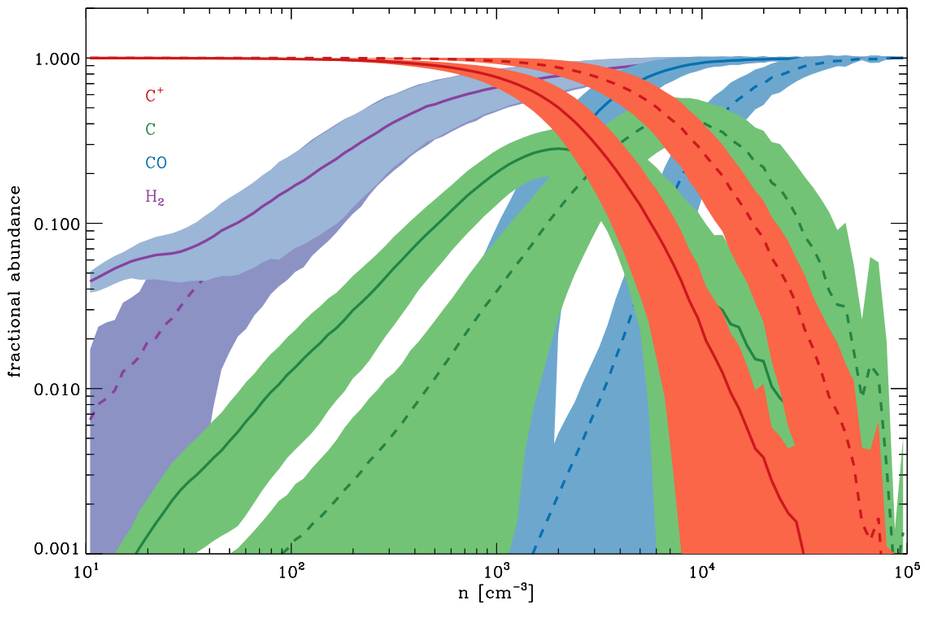
[CII] x 20 **CO (1-0)**

[CI] (1-0) x 2

[CI] (2-1) x 2



Abundance Variations with Density



The plot on the left shows how the fractional abundances of H_2, C^+, C and CO vary with density in our two simulations. We see that by a density of ~100 cm^{-3}, the H_2 fractions are essentially independent of the environmental parameters G_0 and CRIR. However, the carbon-bearing species are sensitive to the environmental conditions, with the factor of 10 change in G_0 and CRIR producing a roughly factor of 10 shift in the density dependancy of the abundance curves. Consistent with the results of Glover et al. (2010) and Clark et al. (2012), we see that the CO abundance only ramps up at densities above 1000 cm^{-3}. Below this density, the overwhelming majority of the carbon is in the form of C^+, despite the cloud being "molecular" in terms of its H_2 content.

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