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Lupus disks with faint CO isotopologues: low gas/dust or high carbon depletion?

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Abstract. With the advent of ALMA, complete surveys of gas and dust in protoplanetary disks are being carried out in different star forming regions. In particular, continuum emission is used to trace the large (mm-sized) dust grains and CO isotopologues are observed in order to trace the bulk of the gas. The attempt is to simultaneously constrain the gas and dust disk mass as well as the gas/dust mass ratio. In this work the observations from the *Lupus disk survey* have been analyzed with thermo-chemical disk models, including radiative transfer, CO isotope-selective processes and freeze-out. We find that CO-based gas masses are very low, often smaller than $1M_{\rm J}$. Moreover, gas/dust mass ratios are much lower than value of 100 found in the ISM, being mainly between 1 and 10. This result can be interpreted either as rapid loss of gas, or as a chemical effect removing carbon from CO and locking it into more complex molecules or in larger bodies. Current data cannot distinguish between the two scenarios (except for sources with detected HD lines), but future observations of e.g. [CI] and hydrocarbon lines will help to calibrate CO-based gas masses and to constrain disk gas masses.

Keywords. astrochemistry – planetary systems: protoplanetary disks – planetary systems: planet-disk interactions – submillimeter: planetary systems

1. Introduction

There have been many attempts to study the bulk content of protoplanetary disks in gas and dust (see e.g., Thi *et al.* 2001; Pascucci *et al.* 2006; Panić *et al.* 2008, 2009; Andrews *et al.* 2012; Boneberg *et al.* 2016; Andrews 2015, as a review), but not in a statistically significant manner. Recently, the Atacama Large Millimeter/sub-millimeter Array (ALMA) has allowed the disk community to carry out complete surveys of gas and dust in protoplanetary disks in different star forming regions in a modest amount of time (Ansdell *et al.* 2016; Pascucci *et al.* 2016; Barenfeld *et al.* 2016). We focus on the first near-complete survey, that has been carried out in Lupus (Ansdell *et al.* 2016), where ~90 disks have been observed at a resolution of 0.3" ($\sim 20 - 30$ au radius for a distance of $150 - 200$ pc). A fraction of these disks were detected in the faint CO isotopologue lines (^{13}CO and C^{18}O). Such lines are commonly used to estimate the total disk gas mass, as they probe deeper into the disk than the optically thick ^{12}CO lines (van Zadelhoff *et al.* 2001; Dartois *et al.* 2003).

The main unknown is related to the conversion of the observed CO mass into total disk mass. A proper modeling of isotope-selective photodissociaton and freeze-out, which regulate CO isotopologues abundances, needs to be done in order to correctly interpret the observations (van Zadelhoff *et al.* 2001; Aikawa et al. 2002; Visser *et al.* 2009; Miotello et al. 2014; Miotello *et al.* 2016). Then, a value for the hydrogen to carbon elemental abundance has to be assumed, but this may not be the canonical value $X_{\rm C}$ =[C]/[H]=1.35×10^{-4} often used. In the case of TW Hya, where hydrogen deuteride was detected by the *Herschel Space Observatory* (Bergin *et al.* 2013), carbon is found to be depleted by 1 or 2 orders of magnitude (Favre *et al.* 2013; Kama *et al.* 2016; Trapman

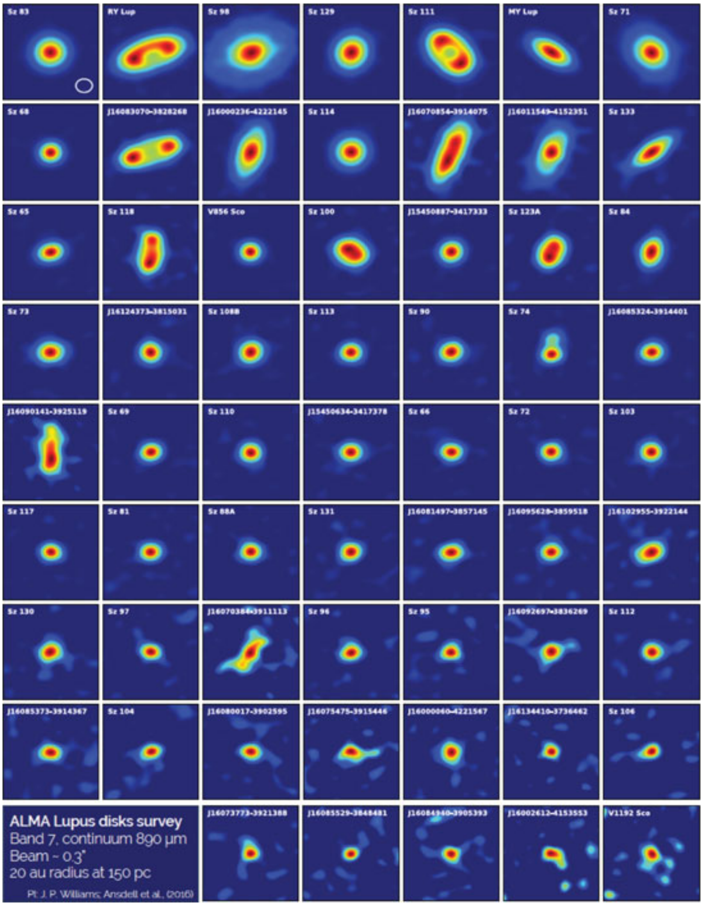

Figure 1. Collection of the disks detected in the continuum at 890 μm in the Lupus star forming region (each panel is $2'' \times 2''$). The resolution is $0.3''$, which corresponds to $\sim$ 20 au at 150 pc (adapted from Ansdell *et al.* 2016).

et al. 2017). This suggest that there may exist a class of disks where CO is not the main carbon reservoir.

2. Results and conclusions

In this proceeding we summarize some of the results obtained by Miotello *et al.* (2017), so we refer the reader to this paper for more detail. The modeling technique developed by Miotello *et al.* (2016) is applied to the ALMA continuum, ^{13}CO and C^{18}O Lupus observations (see Fig. 1). With our modeling procedure we are able to provide disk gas mass determinations also for the disks detected only in ^{13}CO, for a total of 34 objects. Previously, Ansdell *et al.* (2016) have presented an initial analysis for only 10 disks, for which both ^{13}CO and C^{18}O lines are available. This sample is extended and refined in Miotello *et al.* (2017). ^{13}CO alone can be used as a mass tracer only if its line emission are optically thin. We have used the grid of models presented in Miotello *et al.* (2016) to obtain the median of the ^{13}CO $J = 3 - 2$ simulated line luminosities. They can be

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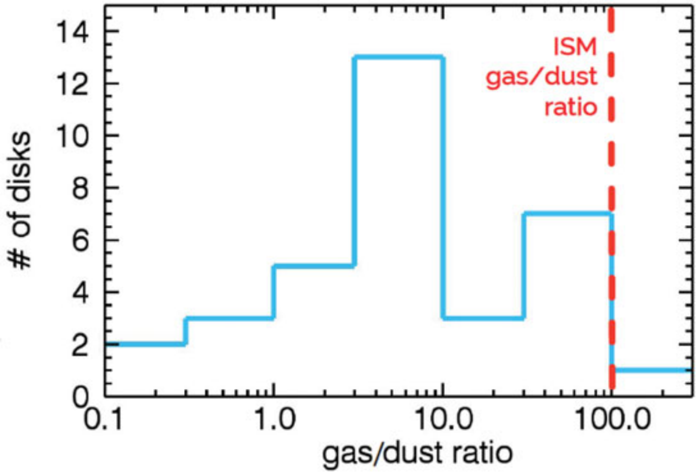

Figure 2. Histogram showing the number of disks presenting different levels of gas-to-dust ratio in the Lupus sample. Only disks detected both in continuum and ^{13}CO are considered (adapted from Miotello *et al.* 2017).

expressed by fit functions of the disk mass.

$$L_y = \begin{cases} A_y + B_y \cdot M_{\mathrm{gas}} & M_{\mathrm{gas}} \leqslant M_{\mathrm{tr}} \\ C_y + D_y \cdot \log_{10}(M_{\mathrm{gas}}) & M_{\mathrm{gas}} > M_{\mathrm{tr}}, \end{cases} \tag{2.1}$$

where $y = 13$ or 18, for ^{13}CO and C^{18}O respectively. The polynomial coefficients A_y, B_y, C_y, and D_y, as well as the transition masses M_{tr} are reported in Table 2 of Miotello *et al.* (2017). The dependence of the emission on the disk mass is linear for masses smaller than a transition point M_{tr}, while it flattens becoming logarithmic for more massive disks. All the ^{13}CO-only detections are in the region of the emission-mass plane where $M_{\mathrm{disk}} < M_{\mathrm{tr}}$, so the dependence is linear. Therefore the fit function can be used to calculate the gas masses of these sources, as ^{13}CO is optically thin.

We derive very low gas masses that are generally lower than 1 M_{Jup}, consistent with Ansdell *et al.* (2016). When compared with the derived dust masses from continuum emission, this translates to low global gas/dust ratios. Fig. 2 presents a histogram of the gas/dust ratio. Only objects for which both the continuum and ^{13}CO were detected are considered in the histogram. For most of the Lupus disks the global gas/dust ratio is between 1 and 10, much lower than the expected ISM-value of 100.

Low CO-based gas masses and gas/dust ratios are usually interpreted as the outcome of physical disk evolution that leads to a loss of gas. An alternative interpretation may be that the CO abundance is lower than what is usually assumed. Volatile carbon could be sequestered from CO to more complex less volatile molecules or being locked-up into larger bodies (Aikawa *et al.* 1996; Bergin *et al.* 2014; Du *et al.* 2015; Eistrup *et al.* 2016; Kama *et al.* 2016).

Current observations of continuum and ^{13}CO are not enough to distinguish between the two scenarios. Future ALMA observations of more complex tracers, such as hydrocarbons, or [CI] lines are needed to calibrate CO-based masses. An alternative method has been proposed by Manara *et al.* (2016) and Rosotti *et al.* (2017) to trace the gaseous disk component, independently from chemistry. This method is based on the simultaneous availability of dust disk mass and mass accretion rates measurement. Manara *et al.*

(2016) recently found for the first time a linear relation between the mass accretion rate using VLT/X-Shooter data (Alcalá *et al.* 2014, 2017) and the disk total mass inferred from the dust in Lupus. A linear correlation between $\dot{M}_{\rm acc}$ and $M_{\rm disk}$ has been theoretically predicted by viscous evolution theory (Hartmann *et al.* 1998). On the contrary, we have found no correlation between mass accretion and the disk masses derived from CO isotopologues lines for our 34 Lupus sources. Assuming that the evolution of all Lupus disks has occurred mainly viscously over the past few Myr, the observed correlation between the mass accretion rate and dust mass found by Manara *et al.* (2016) implies a constant gas/dust ratio of 100. This is a hint to a scenario in which carbon is depleted and this affects CO line emission.

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