

Gas evolution in protoplanetary disks

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Abstract. We present the results of a study of the evolution of the gas and dust in disks around T Tauri, Herbig Ae and Vega-like stars. We observed the two lowest rotational lines of H₂ with the ISO-SWS as well as ¹²CO 3–2 and ¹³CO 3–2 with the JCMT, and CO 6–5 with the CSO. The H₂ lines trace the warm (~ 100 K) inner region whereas the CO lines probe the colder outer disks. Substantial amounts of H₂ have been detected toward T Tauri and Herbig Ae stars, and, surprisingly, also around three Vega-like objects (49 Cet, HD 135344 and β Pictoris). In contrast with previous conclusions derived from CO data, a significant mass of warm gas is found to persist up to ages of several tens of Myrs, suggesting that slow formation of gas-rich giant planets is possible.

1. Introduction

It is well recognized that many low (<1 M_⊙) and intermediate mass (1–5 M_⊙) pre-main sequence stars are surrounded by 10⁻³–10⁻¹ M_⊙ of gas and dust (Mundy et al. 2000). Surveys with millimeter interferometers reveal that the matter is in the form of a disk of radius 100–400 AU in Keplerian rotation (e.g. Dutrey et al. 1996, Mannings & Sargent 2000). The disks contain enough material for the formation of giant planets. Their main constituent —by a factor of 100— is molecular hydrogen (H₂) which can be incorporated in the atmospheres of giant gaseous planets. Direct observation of H₂ is therefore of prime importance, but Earth-based searches are hampered by the severe telluric absorption in the mid-infrared. The *Short Wavelength Spectrometer* (SWS) on board the *Infrared Space Observatory* (ISO) has allowed us to perform the first study of H₂ emission from 15 T Tauri and Herbig Ae stars with disks. In addition, three

older objects —49 Ceti, HD 135344 and β Pictoris— have been observed, so that our objects cover the $(1\text{--}20)\times 10^6$ yr age range.

Current estimates of the disk gas mass rely on CO observations which require a conversion factor between the CO flux and H_2 mass. This conversion factor varies from source to source, depending on spectral type of the central star and the density and temperature structure of the disks. Processes such as photodissociation and freeze-out onto grain surfaces have been invoked to explain the CO “depletion” (Kamp & Bertoldi 2000). Direct observations of the lowest pure-rotational H_2 lines at $17\ \mu\text{m}$ ($J=3\text{--}1$) and $28\ \mu\text{m}$ ($J=2\text{--}0$) probe the (inner) warm region (100–200 K) of disks, the most likely area for the formation of planets. Observations of high- J CO transitions with the JCMT and CSO extend the study to the colder (< 80 K) part of disks. Together with literature data on the millimeter continuum, both the warm and cold gas and dust are probed.

An important constraint on planet formation theories is the timescale of the dissipation of disks (Lissauer 1993). In the core accretion model, the growth of giant planets is slow and limited by the lifetime of the gas, whereas in the disk instability model planets can be built in a very short time provided the disk has a large mass initially. Our observations provide constraints on the evolution of the gas. A short-lived gas disk will also prohibit migration of giant planets triggered by interactions with the disk. Detailed reports can be found in Thi et al. (1999, 2000*a, b*).

2. Observation and Results

The observations carried out with the ISO-SWS suffer strongly from cosmic ray bombardments. The use of dedicated data reduction software which takes advantage of multiple redundancies in the observational procedure allows us to recover the initial sensitivity (Valentijn & Thi 2000). Figure 1 shows examples of obtained spectra. H_2 lines are detected toward many T Tauri and Herbig Ae stars, and, surprisingly, also toward the older objects. The higher S(3) transition is not detected, limiting the amount of hot ($T > 200$ K) gas. The H_2 lines are optically thin, and their ratio gives directly the kinetic temperature assuming LTE. The inferred warm (100–220 K) gas masses are $(0.1\text{--}10)\ 10^{-3}\ M_\odot$, corresponding to 1–10% of the mass derived from the dust 1.3 mm continuum assuming a gas/dust ratio of 100 for the pre-main sequence stars. There is no apparent trend with spectral type. For the Vega-type stars, the fraction can increase to 100%. The CO spectra (cf. Figure 1) exhibit the “double-peak” profile consistent with emission from a disk in Keplerian rotation. Assuming $\text{H}_2/\text{CO}=10^4$ and a gas/dust ratio of 100, the derived “cold” gas masses from ^{13}CO are factors 10–200 lower than the masses deduced from the 1.3 mm dust emission.

3. Discussion

The “warm” H_2 gas appears to constitute the major gaseous component of Vega-like objects, whereas in young objects the “cold” component dominates the gas mass. This cold gas is not well traced by CO, which is substantially depleted

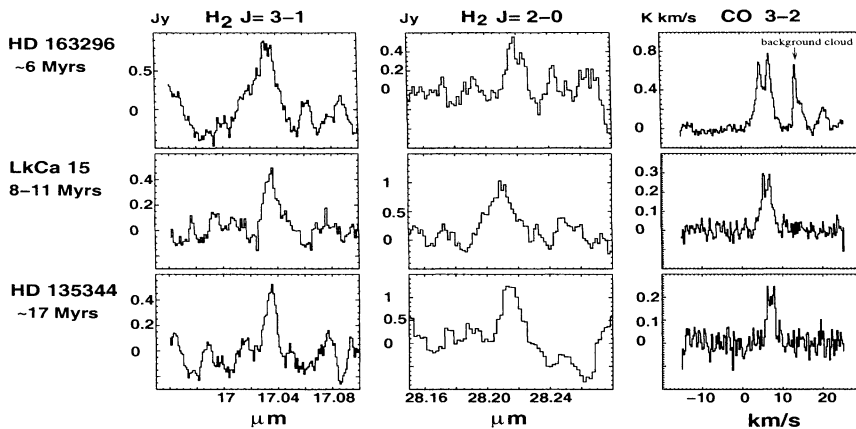


Figure 1. H_2 S(1), S(0) and ^{12}CO 3–2 spectra of three selected objects in our sample. The ages of the stars are estimated using pre-main-sequence evolutionary tracks from Siess, Forestini, & Bertout (2000).

due to photodissociation and freeze-out. The amount of warm gas in pre-main sequence objects is larger than can be explained by current models and more detailed calculations of the heating and cooling processes of the gas and dust need to be considered. No significant evolution of the gas and dust masses is found up to 10 Myrs, but some tendency toward decrease at later times is apparent.

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