Ices, silicates, and gas in FU Orionis objects

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FU Orionis objects (FUors) play a central role in the study of the evolution of young stars. They undergo accretion outbursts that can bring up to about 0.01 solar masses per outburst, therefore providing a significant amount of mass in the pre-main sequence life of a star. We have observed nine FUors with *Spitzer* IRS to detect and model the silicate and ice (e.g., carbon dioxide, water, etc) features and the gas emission lines (e.g., Ne II, H_2, Fe II). Previous Spitzer IRS observations of FUors have shown either silicate features in absorption and ice bands or silicates in emission with no ice bands. This led some authors to propose an evolutionary paradigm in which the former FUors are younger than the latter FUors. This paradigm suggests that the FUor phase may be the link between Class I and Class II sources and that might be a common but rarely observed phase of most young low-mass stars. Our sample of targets show similar features: some targets with deep silicate and ice features in absorption and others with silicates in emission and no ices. In addition gas emission lines are detected in some targets. We present an analysis of the ice component in the *Spitzer* IRS spectra together with the silicate feature. An ongoing analysis will compare the properties of our FUor targets with other known FUors and place them into the evolutionary sequence from Class I to Class II stars.

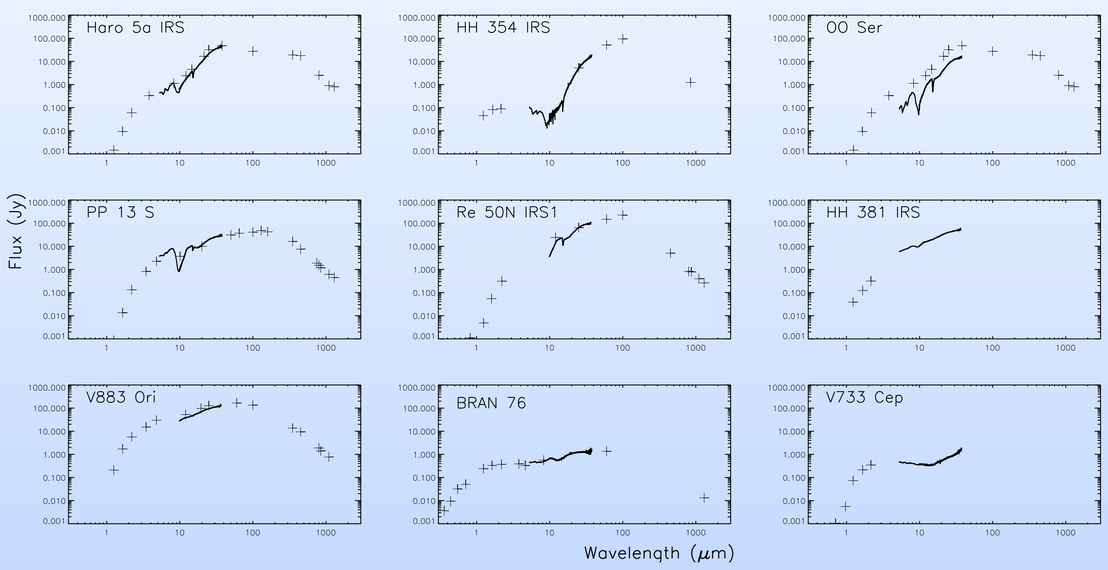

Fig. 1: Spectral energy distributions of our sample of FUors showing the Spitzer IRS spectra (5-40μm) together with published photometry from the near-infrared to millimeter wavelengths. The mismatch between OO Ser photometry and IRS spectroscopy likely originates from the more recent observation date with Spitzer (later in the outburst decay) compared to the older photometry.

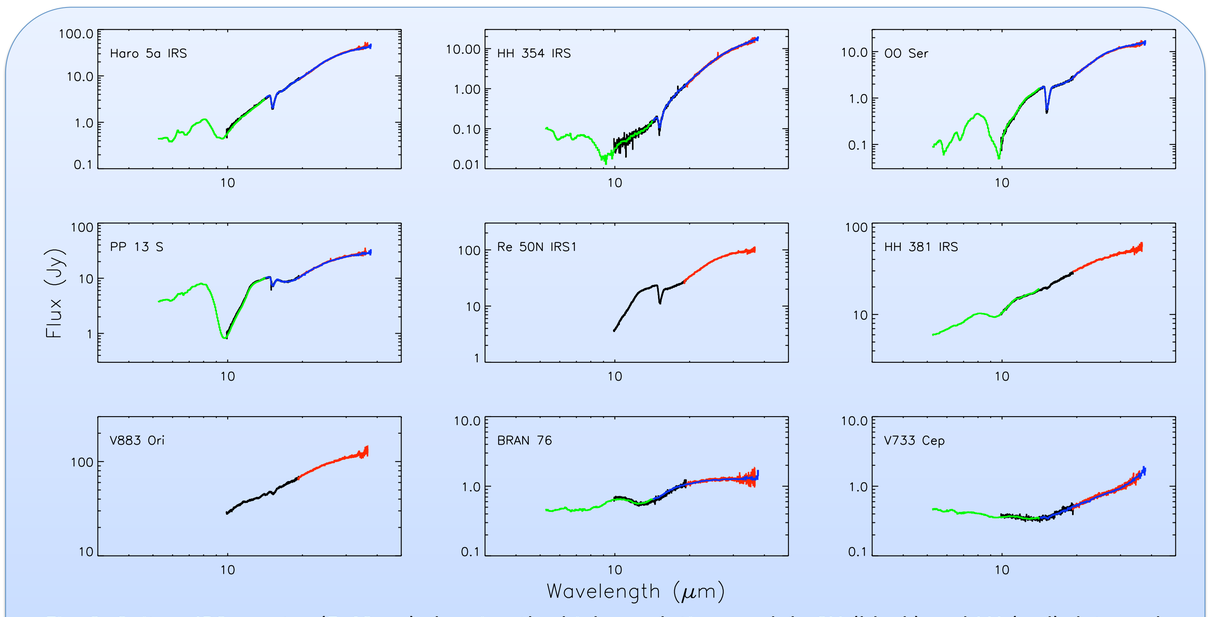

Fig. 2: Spitzer IRS spectra (5-40μm) showing the high-resolution module SH (black) and LH (red) data and the low-resolution module SL (green) and LL (blue) data. Most FUors in our sample show deep absorption features from silicates (near 10μm and 18μm) and from ices (mainly CO_2, H_2O, CH_3OH). Some gas emission lines (mainly [Fe II] at 17.9, 24.5, 26.0, 35.3 μm) are also detected. Note the deep H_2O absorption in Haro 5a IRS, HH 354 IRS and OO Ser, on top of the silicate feature (see Fig 5). In contrast H_2O ices are weaker in PP 13 S, Re 50N IRS1, HH 381 IRS, and V883 Ori. Silicate absorption is also weak in HH 381 IRS and V883 Ori. BRAN 76 shows silicate in emission, while V733 Cep shows no evidence of features in absorption or emission. Quanz et al. (2006) also showed this dichotomy of FUors with deep absorption features and strongly increasing SED and other FUors with emission features and flatter infrared slope.

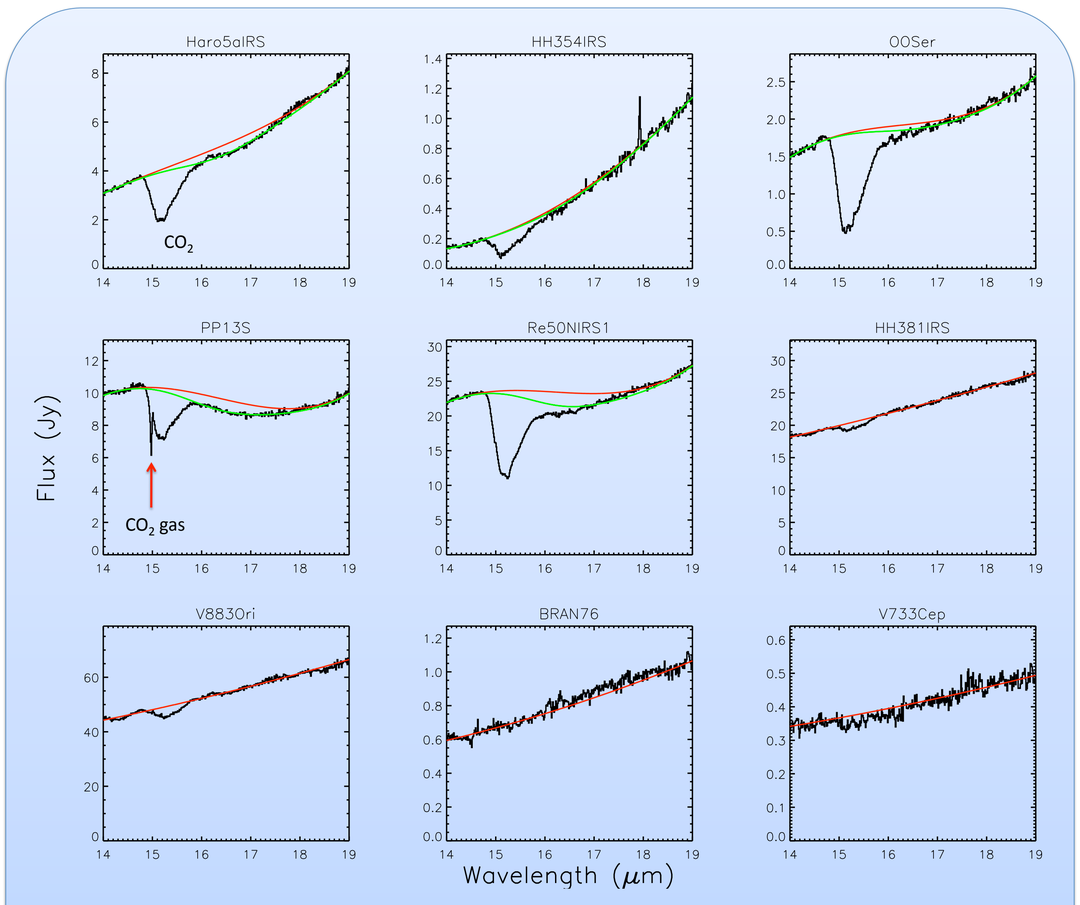

Fig. 3: Zoom of the SH spectra near the CO_2 ice feature. A continuum was obtained with a polynomial of degree N=3 (red curve; HH 381 IRS, V883 Ori, BRAN 76, and V733 Cep needed N=2) to fit the ranges 13.5-14.7 and 18.2-19.5 μm (except for HH 381 IRS and V883 Ori for which 13.5-14.7 and 16.0-17.0 μm were used). In addition, in some cases, a Gaussian function centered on 608 cm^{-1} (16.45 μm) and of FWHM=73 cm^{-1} was added to fit the 16.5-18.2 μm range to account for absorption due to silicates (sum shown as green curve). This method is similar to that used by Pontoppidan et al. (2008). BRAN 76 and V733 Cep show no evidence of CO_2 absorption.

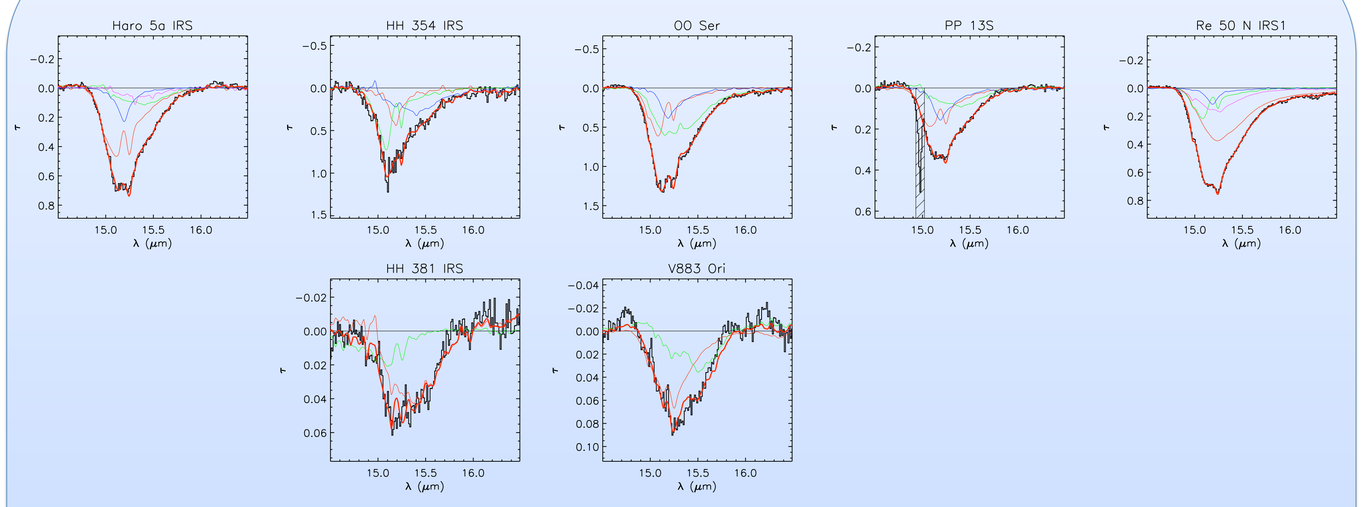

Fig. 4: Absorption depths near 15 μm obtained from $F=F_0e^{-\tau}$, where F is the observed flux density, F_0 is the continuum shown in Figure 3. Note the different ranges in the y axes. Laboratory data of H_2O+CH_3OH+CO_2 mixtures from White et al. (2009) were used to fit the absorption depths from 14.5 to 16.5 μm. The data were fitted with 1, 2, 3, or 4 components, and χ^2 values were used in F tests to determine the maximal number of components to fit the data (using a threshold of 5%). The best-fit sum of components is shown as a thick red curve. The PP13 S data were fitted without the CO_2 fundamental gas line at 14.97 μm since the line likely originates from absorption in the surrounding molecular cloud. Re 50 N IRS1 and OO Ser also show weak CO_2 gas absorption. A future fitting test will also remove the 14.93-15.02 μm range to see if results change (the lab data include sometimes weak CO_2 gas absorption due to impurities, which might bias the fitting results). The fits include one model with two absorption features due to ice mixtures (CO_2≈30%) at high T (110-135K). Pontoppidan et al. (2008) attributed such profile to pure CO_2 ices. A second component with an absorption centered around 15.2 μm is due to H_2O-rich (≈80%) ices at high T (150-160 K). A third component was also often needed to fit the red wing and was in general well-modeled by CO_2-poor (≈50% H_2O and ≈50% CH_3OH) ices at medium T (55-65 K).

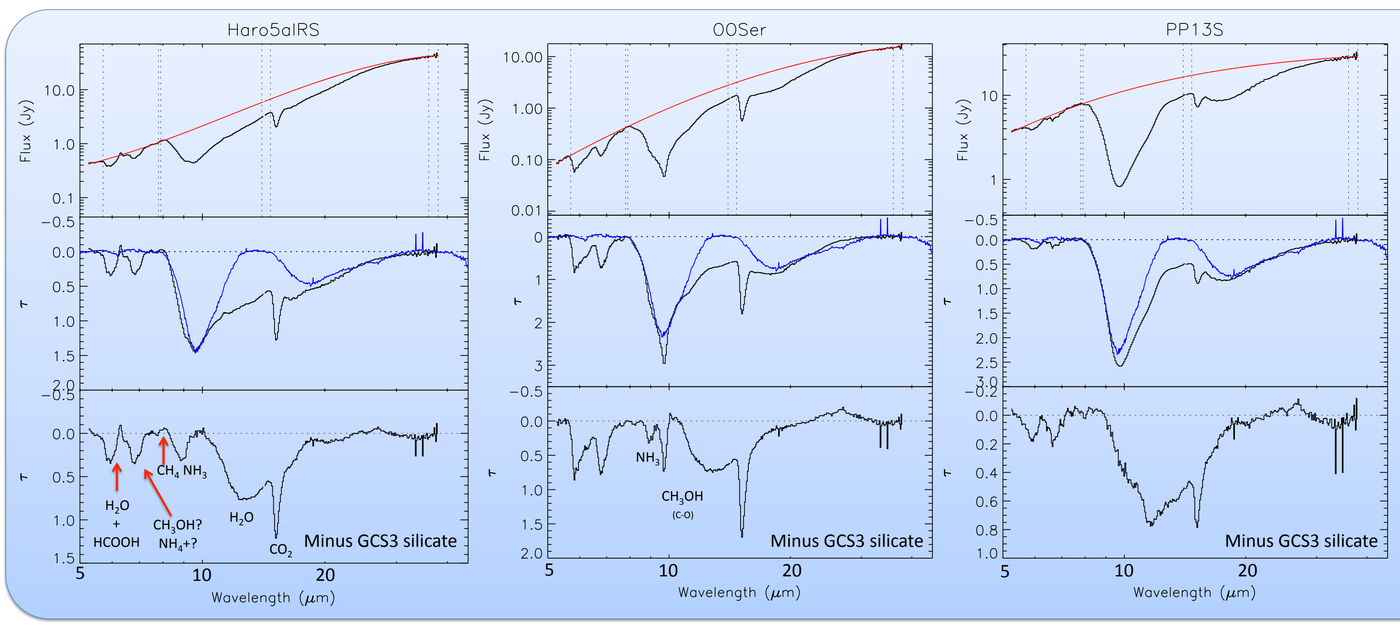

Fig. 5: Preliminary analysis of the ice features. A log λ-log F_ν polynomial of degree 3 was fitted to the SL spectra for the ranges ≤5.7 μm, 7.8-7.9 μm, 14.0-14.7 μm, and 36-38 μm (dotted lines). The method is adapted from Zasowski et al. (2006). The optical depth was derived from this continuum (middle panel). The optical depth of galactic source GCS3 (Kemper et al. 2004), typical of the interstellar medium silicates, is overplotted in blue (multiplied by 0.625 for PP13 S to match the derived optical depth). The optical depth after subtraction of the silicate component is shown in the bottom panel. H_2O absorption is clearly visible from 10-20 μm and around 5.7 μm. Other features are also detected apart from the CO_2 features at 15 μm. The analysis will continue to derive the ice properties (column density, etc), e.g., using laboratory data (e.g., Mastrapa et al. 1999).

•Kemper, F., et al. 2004, ApJ, 609, 826
•Mastrapa, R., et al. 2009, ApJ, 701, 1347
•Pontoppidan, K.M., et al. 2008, ApJ, 678, 1005
•Quanz, S.P., et al. 2006, ApJ, 668, 359
•White, D.W., et al. 2009, ApJS, 180, 182
•Zasowski, G., et al. 2009, ApJ, 694, 459

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