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Evidence of Episodic Accretion in Spitzer IRS Spectra of Low-Luminosity Embedded Protostars

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We present *Spitzer* IRS, SH mode spectroscopy toward 21 young stellar objects (YSOs) with luminosity lower than 1 $L_\odot$ (4 with luminosity lower than 0.1 $L_\odot$). While the standard star formation model predicts protostars to have a luminosity higher than 1.6 $L_\odot$, *Spitzer* Legacy Project, From Molecular Cores to Planet Forming Disks (c2d) survey shows that 59 % of the 112 embedded protostars have luminosity lower than 1.6 $L_\odot$. One possible explanation is that mass accretion is not a constant process. If accretion is episodic, sources that currently are low luminosity may have had much higher accretion rates, and thus luminosities, in the past. In that case, imprints of the high luminosity stage in low luminosity YSOs would support the idea of episodic mass accretion. Evidence may be found in their 15.2 μm CO_2 ice features. Pure CO_2 ice can be formed only at elevated temperatures and thus higher luminosity. Current internal luminosities of YSOs with $L \leq 1$ $L_\odot$ do not provide such conditions. We analyze 15.2 μm CO_2 ice bending mode absorption lines in comparison to laboratory data. Preliminary analysis indicates that the low luminosity YSOs may harbor pure CO_2 ice components. A detailed analysis is ongoing and the results are presented here.

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1. Introduction

The *Spitzer Space Telescope* discovered a set of Very Low Luminosity Objects (VeLLOs; Young et al. 2004; Bourke et al. 2006; Dunham et al. 2006; Dunham et al. 2008), defined by di Francesco et al. (2007) to have luminosity lower than 0.1 $L_\odot$. The luminosity of accretion is given as $L_{acc} \propto M_\star \dot{M}$, where $M_\star$ is the mass of the star and $\dot{M}$ is the mass accretion rate. For accretion at the standard rate onto an object at the stellar/brown dwarf boundary, $L_{acc} \sim 1.6$ $L_\odot$ (Shu et al. 1987). The low luminosity must arise from a low mass accretion rate or a very low mass of the young stellar object. More generally, the range of luminosities of embedded Class 0/I sources is very large (Evans et al. 2009), and this range is not predicted by any model of steady accretion.

This wide range of luminosity is predicted by models of episodic accretion (Dunham et al. 2010). In this picture, accretion from the envelope is not transferred smoothly to the star, but instead builds up in the disk. When the embedded disk of a young stellar object becomes gravitationally unstable, the mass accretion to the central protostar increases (Vorobyov & Basu 2005). Once episodic accretion happens, the mass accretion rate gets higher, which results in high accretion luminosity.

Evidence can be found in molecular spectra in the gas and ice phase of low luminosity sources. Pontoppidan et al. (2008) analyzed the general shape of the 15.2 μm CO_2 ice bending mode spectrum toward 50 embedded young stars. The 15.2 μm CO_2 spectrum can be decomposed to the multiple components including a pure CO_2 ice component. Pure CO_2 ice can form by two processes. One is CO_2 segregation out of a CO_2-H_2O mixture. The other is a distillation process, in which CO evaporates from a CO_2-CO mixture, leaving pure CO_2 behind. The former process occurs at a high temperature (50 - 80 K) and the latter occurs at a lower temperature (20 - 30 K). Both pure CO_2 formation processes are irreversible (Hagen et al. 1983), since the bond between pure CO_2 ices is the most stable phase. Once the pure CO_2 ice has formed, it will not disappear unless evaporates. The past heating of the core can effect on the 15.2 μm CO_2 ice bending mode spectrum.

The total amount of CO_2 ice is another indicator. The episodic accretion scenario gives multiple long periods of low luminosity (Dunham et al. 2010) instead of the short period of low luminosity that the continuous accretion model predicts (Shu 1977; Young & Evans 2005). As a result, episodic accretion provides more time to form ice. The total amount of CO_2 ice can vary depending on the accretion scenario. With chemical modeling, the accretion scenario can affect the total amount of CO_2 ice, and can explain the observed total of CO_2 ice.

2. Observations

We observed a sample of 19 embedded YSOs with luminosities in the range between 0.08 - 0.69 $L_\odot$. We used Spitzer IRS, Short-High (SH) mode spectroscopy to study the 15.2 μm CO_2 ice feature. Currently existing envelopes around the selected sources in this study are not warm enough to form a pure CO_2 ice component either by distillation or segregation.

3. Results

We present one example in Fig. 1. IRAM04191-IRS (André et al. 1999; Dunham et al. 2006)

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is a VeLLO, which has current luminosity lower than 0.1 $L_\odot$. The current internal luminosity of a VeLLO with $L < 0.1$ $L_\odot$ does not provide the conditions needed to produce pure CO_2 ice at a radius where a typical envelope begins. Significant amounts of pure CO_2 ice would signify a higher past luminosity. Using laboratory data, we find evidence for pure CO_2 ice toward 15 out of 19 young low luminosity sources. Eight sources show a significant double peak in the optical depth, which provides unambiguous evidence for pure CO_2 ice. The presence of the pure CO_2 ice component indicates higher dust temperature and hence higher luminosity in the past.

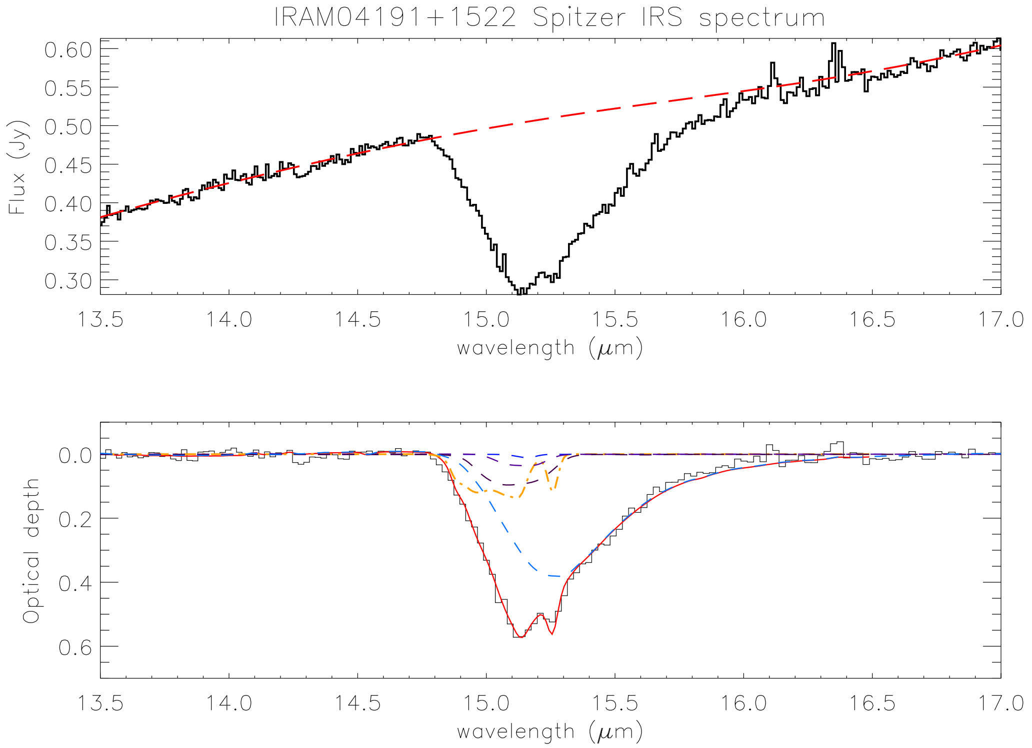

Figure 1: CO_2 ice component analysis of VeLLO, IRAM04191+1522, with laboratory data. The upper panel shows observed flux vs. wavelength. The lower panel shows the component analysis. The black solid line is the observed optical depth at 15.2 μm; the yellow line is the pure CO_2 ice component, the blue line is the water rich CO_2 ice component, and purple lines are the CO-CO_2 mixture ice components. The sum of all the components is plotted in red. The source has the pure CO_2 ice component, and shows a significant double peak.

In addition to the evidence for pure CO_2, the total amount of CO_2 ice, including that in mixed ices, can be explained by long periods of low luminosity between episodic accretion bursts, as predicted in an episodic accretion scenario. We use the evolutionary chemo-dynamical model by Lee et al. (2004) to test this idea. The model calculates the chemical evolution of a core from the prestellar core to the embedded protostellar core stage. At each time step, the model calculates the density profile, the dust temperature, the gas temperature, and the abundances self-consistently. We used two kinds of luminosity evolution models: continuous accretion model and episodic accretion. Also, we included an additional pathway to CO_2 ice from CO gas, and tested the chemical evolution model with and without the chemical network. Observed column densities show the best match with the range of episodic accretion with conversion of CO ice to CO_2 ice.

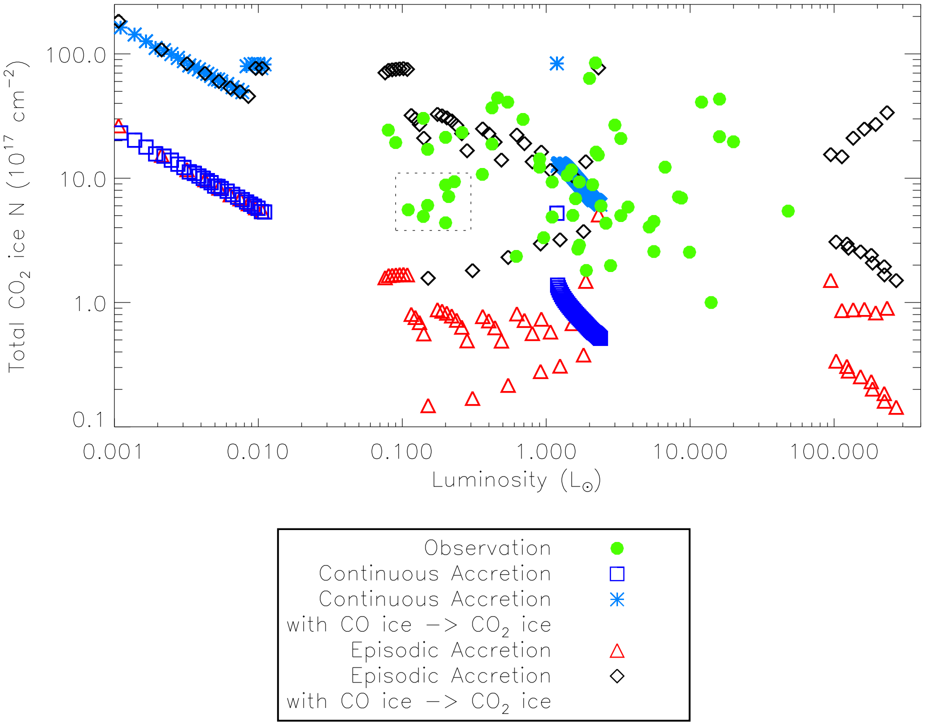

Figure 2: The column densities from observations and the chemical models are plotted versus luminosities. Green points are observations from the current study and the study of Pontoppidan et al. (2008). Together, the studies cover the luminosity range 0.1 $L_\odot$ to 100 $L_\odot$. Blue points are predictions from a continuous accretion model, red points are predictions from an episodic accretion model, and black points are from an episodic accretion model including 10% conversion of CO to CO_2 ice during each cycle. Observed column densities show best match with the range of episodic accretion with conversion of CO ice to CO_2 ice.

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