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Low-Mass Stellar Objects: The Early Years Near-to-Mid-Infrared Spectrographic Studies of Class I Protostellar Systems in the Taurus-Auriga Region

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Appendix E -

UNIVERSITY HONORS PROGRAM
SENIOR PROJECT - APPROVAL

Name: Gail Zasowski

College: A+S Department: Physics

Faculty Mentor: Dr. Mike Guidry

PROJECT TITLE: Low-Mass Stellar Objects: The Early Years

Near- to Mid-Infrared ~~Step~~ Spectrographic Studies of Class I

Protostellar Systems in the Taurus-Auriga Region

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

Signed: M W Guidry, Faculty Mentor

Date: May 11, 2005

General Assessment - please provide a short paragraph that highlights the most significant features of the project.

Comments (Optional):

Accepted for digital archive 7/12/05

Low-Mass Stellar Objects: The Early Years
Near- to Mid-Infrared Spectrographic Studies of Class I Protostellar Systems in the Taurus-Auriga Region

Gail Zasowski
University of Tennessee Honors Program
May 2005

Advised by Dan Watson (University of Rochester)

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Abstract

The study of young stellar objects (YSOs), and their accompanying dust/gas envelopes and disks is a significant and rapidly growing area in the field of astrophysics. Using spectroscopic data from the new Spitzer Space Telescope, I analyzed several Class I protostellar sources to identify characteristics that could be used in modeling these objects. First, the spectra were extracted from the raw Spitzer data and put into usable format. Then each source was fitted with representations of the spectral continua; these were used to calculate optical depths of the major peaks and features. Plotting these data revealed several trends, such as the close correlation between H_2O and CH_3OH ices. Laboratory ice spectra were fit to the strong 15.2μm CO_2 feature of some objects. Much work remains to be done before a comprehensive understanding of these sources is reached.

Background

Current theory maintains that stars form when a shockwave, for example, from a supernova, or other perturbation passes through a clump of interstellar gas and triggers a collapse. The precise mechanics of cloud collapse are complicated, but the conditions necessary for such a collapse to occur can be approximated by the Jeans Mass, or the minimum mass necessary for a local cloud to self-collapse:

$$M_J = \left(\frac{5k_BT}{mG}\right)^{\frac{3}{2}}\left(\frac{3}{4\pi\rho}\right)^{\frac{1}{2}}$$

for a cloud of a given T (temperature), m (average molecular mass), and ρ (local density)[1]. Inhomogeneities in the original cloud lead to fragmentation and more localized collapses, producing the crowded star nurseries we often observe. The infall time for a locally homogeneous cloud can be approximated by[2]

$$t_{ff} = \left(\frac{3\pi}{32G\rho_0}\right)^{\frac{1}{2}}$$

Notice the inversely proportionate dependence on density. This indicates that clouds collapse most quickly where they are densest, i.e. in the middle, leaving the less dense, outer layers to fall in more slowly. Thus a spheroidal envelope of cold, primordial matter remains, surrounding the more tightly-packed central object.

This object contains both the protostar, which eventually accretes enough mass to ignite nuclear fusion through gravitational contraction, and its accretion disk. The disk is a result of the conservation of angular momentum. All interstellar molecular clouds have some inherent angular momentum, and as collapse occurs, the central dense clump can pull material in along the axis of rotation much more easily than perpendicular to it. This produces a relatively flat disk of gas and dust lying in the plane perpendicular to the axis of rotation. The disk itself undergoes evolution through the processes of accretion and radiative heating, and studies of the stages of disk evolution reveal a great deal about the formation of the system as a whole. The "class" of these objects indicates how evolved their disks are. For example, a Class I has a thick, raw disk and envelope, while a Class II shows more advanced dust grain processing. As time passes, envelope and disk material is accreted by the star, formed into larger objects such as planetoids, or dissipated into interstellar space by solar forces. Thus the entire process ends with the bare star and its small orbiting masses, an image with which we are familiar. Some models predict that this could take as short as a few million years to complete[3].

The most efficient way to study these objects is through infrared astronomy, since the effective temperature of the low mass stars formed by this process is on the order of 5000 K. They are simply not hot enough to emit usable amounts of energy in the visible or higher-frequency parts of the electromagnetic spectrum. Another overwhelming advantage to observing in the infrared is that it allows us to see the dust and molecular matter surrounding the protostars. Cold material like this scatters a great deal of short wavelength radiation and absorbs at longer wavelengths, so observing infrared spectra is ideal for determining the composition and other characteristics of the envelopes and disks.

Partly to this end, the Spitzer Space Telescope (originally SIRTF: Space Infrared Telescope Facility) was launched in August 2003. The telescope, containing instruments sensitive in the infrared wavelengths of 3-180μm, was placed in an Earth-trailing, heliocentric orbit to isolate it from our planet's strong thermal emissions. A cryogenic cooling system maintains a temperature of around 5.5 K, further reducing the unwanted signature of the instruments' own thermal noise. The Infrared Spectrograph (IRS) on board is used by many scientific collaborations to study a variety of objects in the 5-40μm range, including protostars and protoplanetary disks[4].

It was my good fortune to secure an internship with members of the Spitzer IRS Disks team, which oversees all stages of the study of disks/envelopes, from observations made using the IRS to eventual modeling of object evolution. My research is therefore not only part of a large current study, but an ongoing project in itself—one into which I have invested a great deal of work and hope to continue into graduate school. So the methods and results presented here are by no means conclusive, but they do represent several months of hard work and continual learning.

Procedures

Before any analysis of data can be made, the data must of course be put into a usable format. A spectrograph operates by recording light passed through a diffraction slit, thus allowing a measurement of intensity as a function of wavelength. Unfortunately, obtaining useful spectra from a diffraction slit on a telescope is not quite as simple as doing it in a lab. The preliminary calibrations and processing on the raw spectral telescope data can be done immediately by computer; due to the uniqueness of each source, however, automatic data refinement cannot handle the entire process. To solve this, the IRS team uses the Spectral Modeling, Analysis, and Reduction Tool (SMART), developed by team members at Cornell University specifically to reduce Spitzer data[5]. It is a relatively clumsy program that has since been largely supplanted by simpler IDL scripts, but the conceptual process is the same.

Prior to extracting any flux information from the data, I needed to remove background noise, generally from other stars or events like cosmic ray hits, to ensure that the light I extracted truly was from my intended source. To do so, I subtracted images that had been taken while the slit was stationary, thus canceling out the constant background, or "sky." Then I looked at the intensity as a function of spatial distribution on the slit and, depending which calibrators I intended to use later, instructed the computer how much of the intensity peak to extract. This produced a plot of raw flux versus wavelength.

Many errors, including both processing and telescope characteristic errors, were still present, so I multiplied the spectrum with a relative spectral response function (RSRF), which is a calibrator made from telescopic observations of a photometric standard star such as Alpha Lacertae or Ksi Draconis. Additional processing steps included trimming and scaling in specific places to counteract recurring errors, often due to the telescope itself. See Figure 1.

Once a spectrum was reduced and I deemed it reliable, the next step was to calculate optical depths of the features of interest. Optical depth is a measure of the opaqueness of a material at a given wavelength interval. For the purposes of this study, optical depths serve as measures of how much material, absorbent at those particular wavelengths, is present between Spitzer and the luminous star. After accounting for intervening interstellar CO clouds and the like, that material is assumed to be located around the stellar system in question.

When looking at an actual spectrum, of course, a high optical depth appears as a deep absorption feature; any numerical values must be calculated relative to the stellar continuum that the material is absorbing. So I began by fitting mathematical models of the stellar continua to the spectra. These models, called spline fits, give a "base" from which to calculate the optical depth using basic radiative transfer equations. See Figure 2.

As mentioned above, various stages of these general procedures have been modified and streamlined in recent months, but a background understanding is essential, especially in order to handle and use less-than-perfect data.

Analysis

The processes of data reduction and feature strength calculation are preparation for applying more complex science to actually understand these objects.

The first type of analysis I considered was a search for correlation among many different characteristics of the objects. I calculated optical depths for several of the more prominent and interesting features—namely, the 6.0μm H_2O ice line, the 6.8μm organic ice line, the 7.7μm CH_4 ice line, the broad 9.7μm silicates feature, and the 15.2μm CO_2 ice line. These I plotted against each other and against other object features such as redness, location, and disk inclination. Redness was calculated by sampling the flux at 8, 14, and 25μm, researching the H-band (1.6μm) and K-band (2.6μm) fluxes in catalogues[6], and then taking various ratios.

Some findings await further work and publication, but two interesting results are presented here. First, there is a very tight correlation between the relative optical depths of the 6.0μm H_2O and 6.8μm organic (theorized to be CH_3OH or "methanol")[7] ices. Looking at other young stellar object studies shows that this relationship holds true in other mass classes of stars[8]. See Figure 3. The consistent similarity in abundance suggests that the two compounds form in the same location and by similar mechanisms.

Fitting laboratory spectra to these features to identify exact composition and temperature will help greatly in modeling these mechanisms.

A more surprising result is the apparent lack of correlation between CO_2 ice and amorphous silicates. It had been postulated that CO_2 ice formed when dust grains covered in CO were heated by stellar radiation in the disk, so the two should display a fairly constant ratio of abundances. To the contrary, I found no such close relationship, or indeed any relationship at all. My results agree with data catalogued by authors of other studies[8]. See Figure 4. However, when both features are plotted against disk inclination (as revealed in photographic images from various other instruments), some intriguing trends emerge[7]. First, the 10μm silicate feature varies greatly with disk inclination, from barely present in face-on disks to extremely deep in edge-on objects. This supports the theory that the silicates, both amorphous ones and older, more crystalline grains, reside primarily in the disk, as expected. However, the 15.2μm CO_2 feature appears strongly in all Class I objects, regardless of disk inclination; it seems to depend only on the overall intensity of the source. This is strong evidence for the existence of the CO_2 in the outer, spheroidal envelope surrounding the more asymmetrical disk. While not in agreement with original hypotheses, this model does fit more closely with the proposed thermal distribution of the system.

The second focus of my analysis was the particular composition and temperature of the ices themselves. I first chose to examine the CO_2 feature because of its strength and plentiful appearance, and because close study could reveal a great deal of information about the earliest, least-evolved portions of the protostellar systems. Obtaining laboratory ice spectral data from the Leiden Observatory in the Netherlands[9], I rescaled them to match my source spectra and then experimented with various combinations of compounds and temperatures. I found that, as a first approximation, a 1:1:1 combination of H_2O, CH_3OH, and CO_2 ices in a narrow range of temperatures from 116 to 118 K most accurately mimics the structure of the observed feature. See Figure 5. Obviously, much work remains to be done, but this provides a good starting point for more sophisticated models.

As mentioned earlier, this is a work in progress. Several new advancements in the automated computer processing have necessitated manual re-reduction of many sources and have produced numerous decent spectra that were earlier deemed unusable. Enough information lies hidden in the data already processed to keep one busy for a long time, and new information appears constantly. This is a very exciting time for the field.

References

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[6] Kenyon, S.J & Hartmann, L. 1995, ApJS, 101, 117
[7] Watson, D., et al. 2004, ApJS, 154, 391W
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Alexander, R.D., et al. 2003, A&A, 401, 613
[9] Ehrenfreund, P., et al. 1999, A&A, 350, 240

Figures

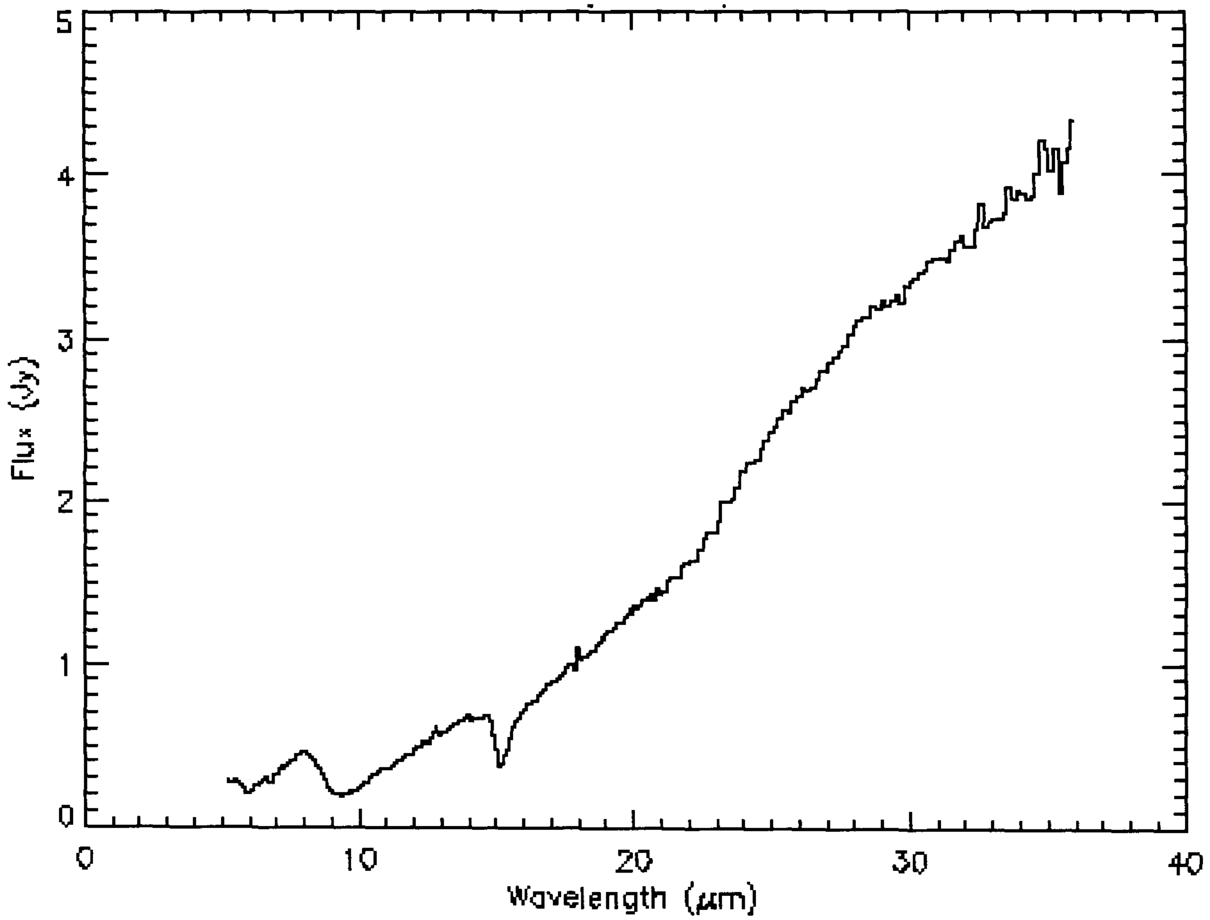

Figure 1. A sample of a Class I spectrum. Notice the strong CO_2 ice feature at 15.2μm, the broad amorphous silicate feature around 9.7μm, and the smaller H_2O and CH_3OH features at 6.0 and 6.8μm, respectively.

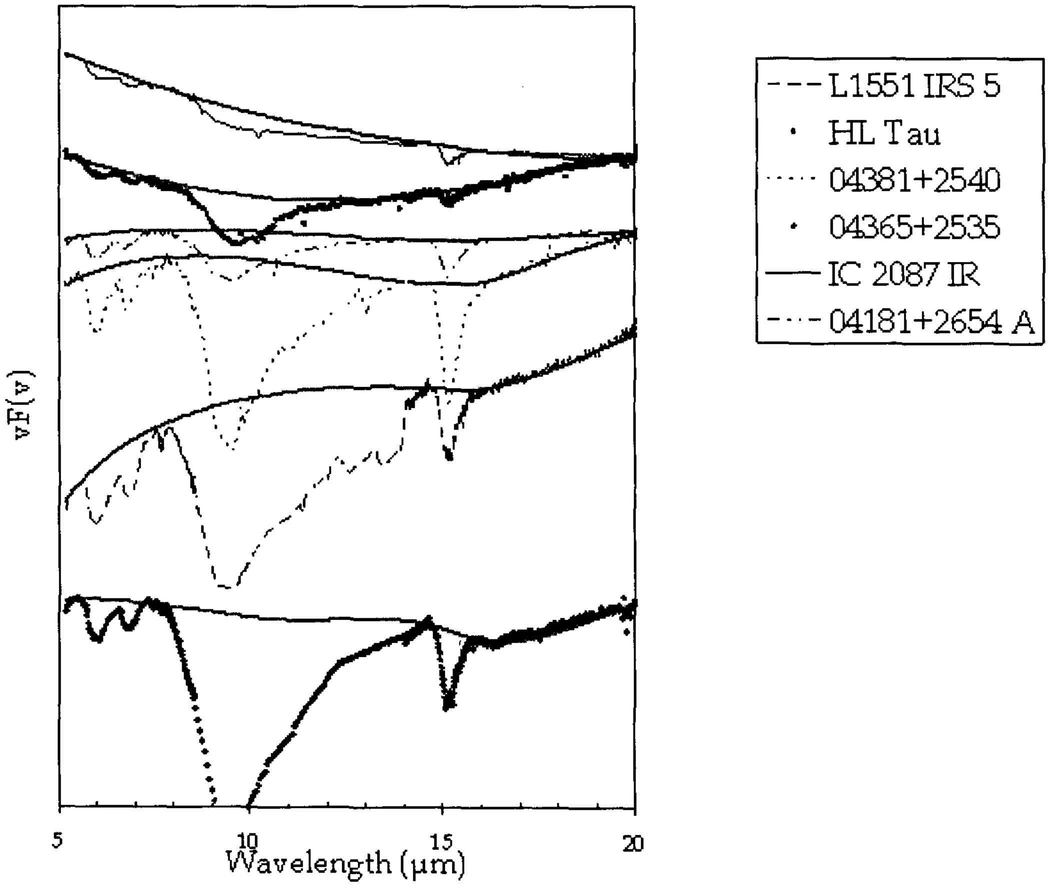

Figure 2. Some spline fits.

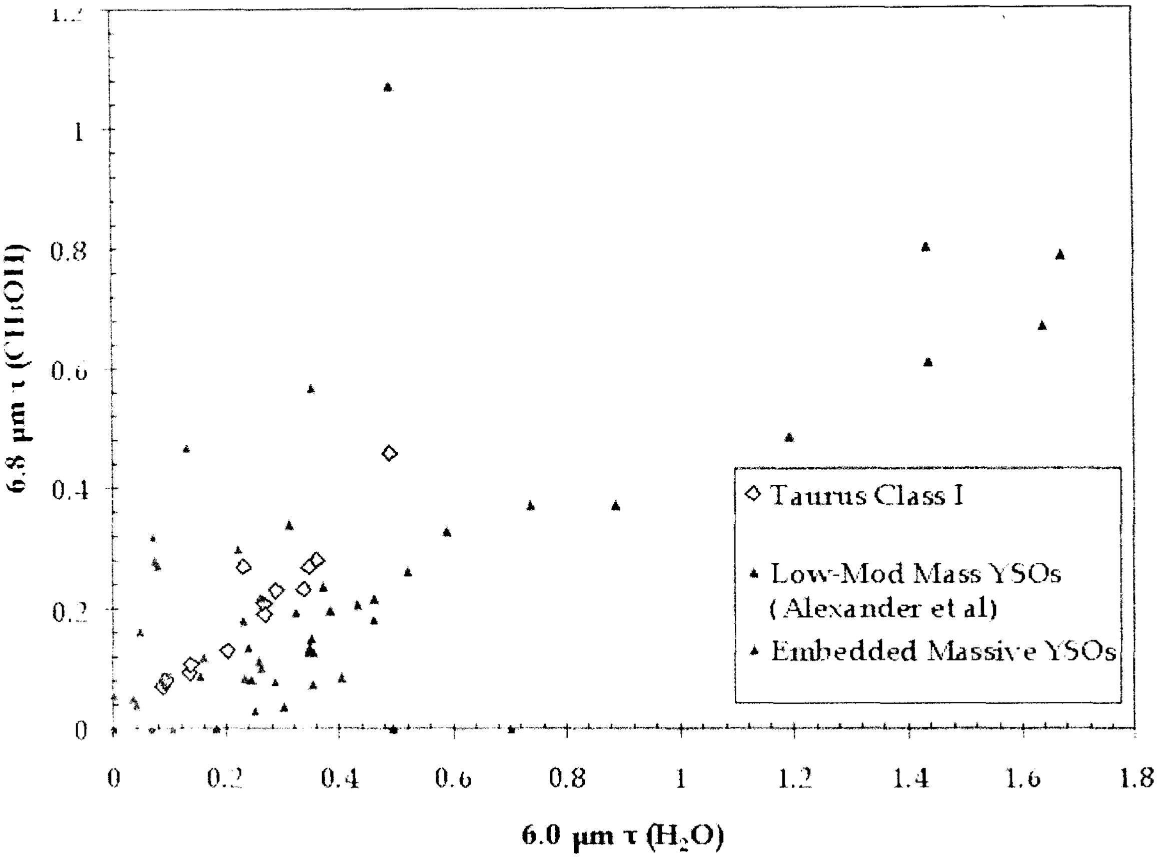

Figure 3. A plot of water ice optical depth (τ) versus methanol ice optical depth. Notice the close correlation. [The embedded massive YSOs should be attributed to Gibb et al.]

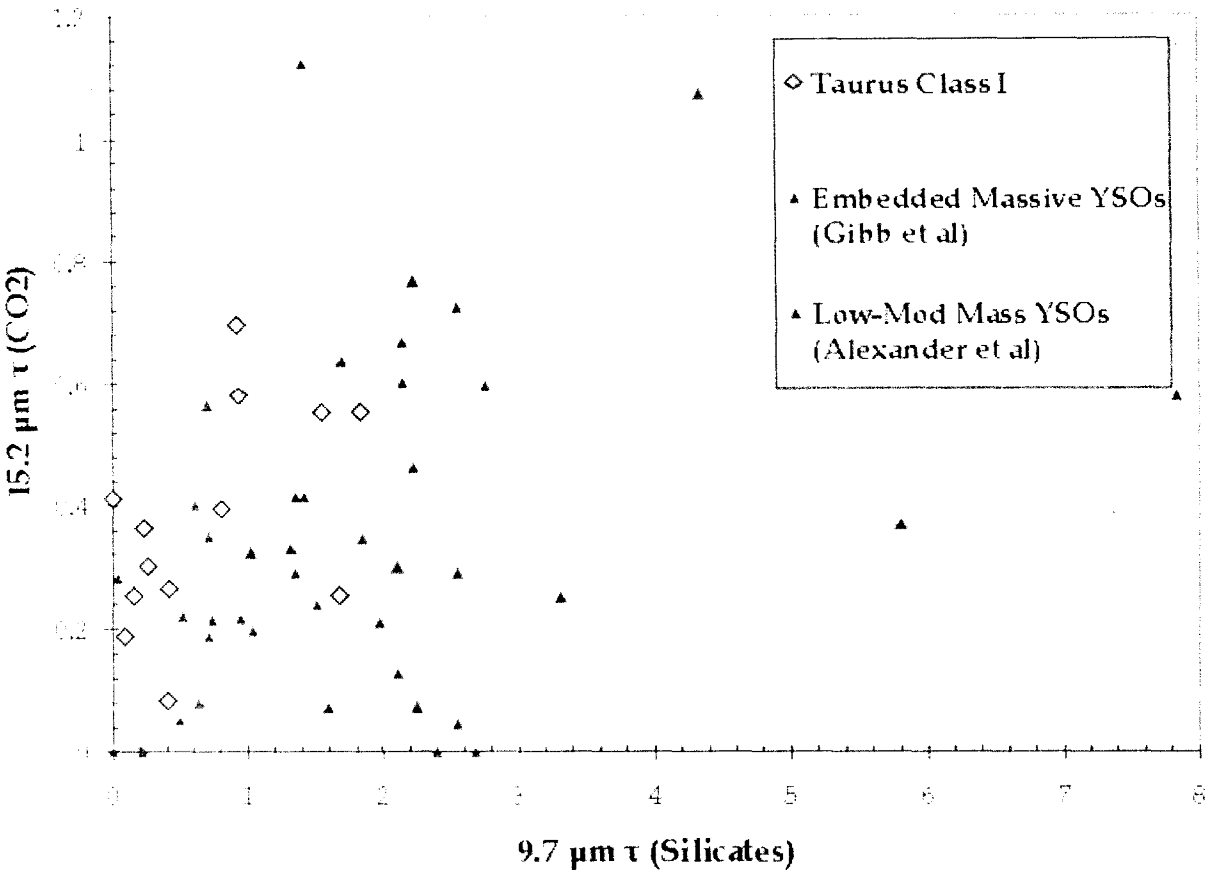

Figure 4. A plot of 9.7µm silicate optical depth verses 15.2µm CO_2 ice optical depth. Notice the lack of correlation in any of the studies.

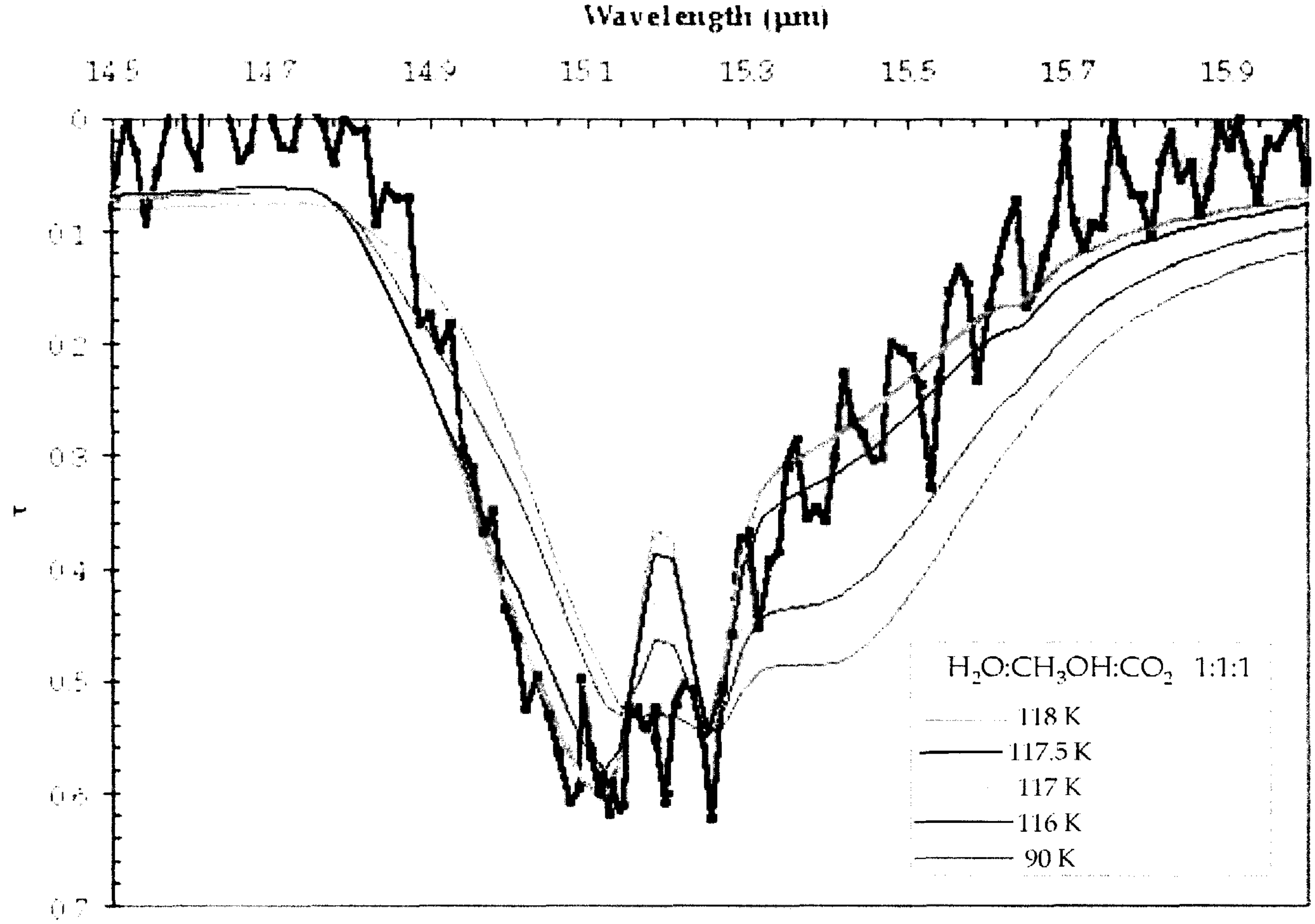

Figure 5. A preliminary ice fit to source L1551 IRS5, showing the temperature dependence of an ice mixture of H_2O, CH_3OH, and CO_2.[9]

Date: Tue, 12 Jul 2005 16:00:59 -0400
From: Mike Guidry <guidry@utk.edu>
Subject: Re: Archiving Senior Project of University Honors Student?
To: Peter Höyng <hoeyng@utk.edu>
Reply-to: guidry@utk.edu
Original-recipient: rfc822;hoeyng@mail.utk.edu

Peter,

Definitely Gail Zasowski's project should be archived.

Mike

On Wednesday 08 June 2005 18:11, you wrote:
> Dear colleagues:
>
> Recently one of your students finished her/his
> senior project as a requirement for graduating as
> a University Honors student. Thanks for making
> this happen!
>
> All of these students have their senior project
> digitized so that Hodges Library can archive them
> as part of the internet.
>
> To make sure, I want to double check with you
> whether you recommend this project to be
> digitally catalogued and archived by Hodges
> Library and made widely available.
>
> I hope to hear from you asap and thank you again
> for your active support of the University Honors
> Program!
>
> With kind regards,
> Dr. Peter Höyng

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