Measuring Gas Accretion onto Orion Protostars

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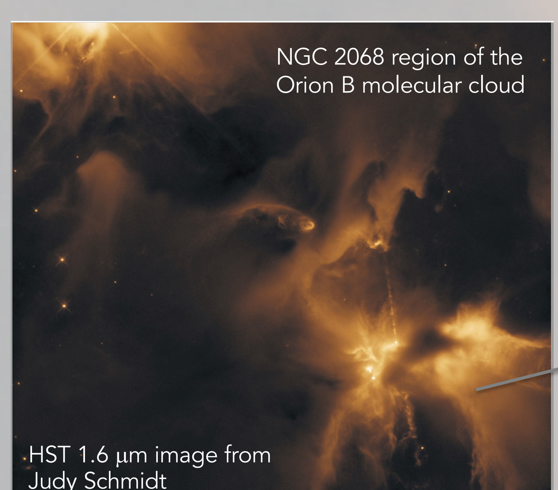
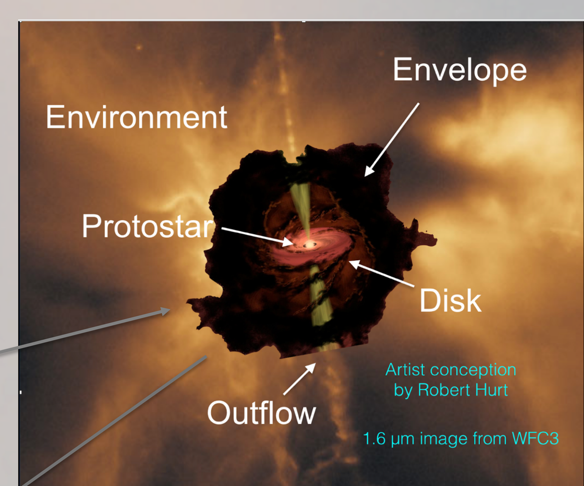
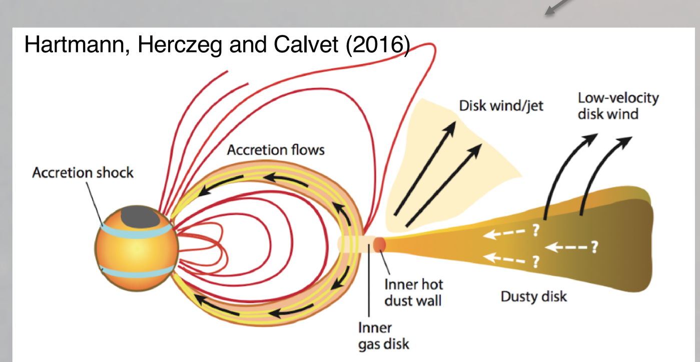
Abstract

A fundamental problem in star formation is understanding how stars accrete mass. Understanding the history of accretion during the protostellar phase is a necessary step towards understanding the origin of stellar mass and the initial mass function. Using near-IR (0.8-2.5 µm) spectra from SpeX on the IRTF, this work draws from observations of 29 protostars, nascent stars still undergoing active mass accretion, identified by the Herschel Orion Protostar Survey (HOPS). The goal is to measure the luminosity generated by mass accretion via the Brackett-gamma emission line in order to determine what percentage of the total luminosity is due to accretion. Line fluxes in multiple hydrogen lines are needed to make a correction for extinction, and 14 protostars in the sample have detections in multiple transitions. For these protostars, which are primarily more evolved Class I and flat-spectrum protostars, 7 of the 14 have less than 50% of their luminosity from accretion.

Measuring Protostellar Accretion using Near-IR Spectroscopy







Background: During magnetospheric accretion, infalling gas from the proto-stellar envelope lands on the disk and is channeled along magnetic field lines onto the central protostar.

The energy radiated by the gas as it lands on the star is the accretion luminosity, or L_{acc}.

Rationale:

- Total bolometric luminosity, L_{bol}, is the sum of the intrinsic luminosity of the protostar and Lacc.: $L_{bol} = L_{acc} + L_{int}$.
- The hot gas in the accretion flows emits in hydrogen lines.
- The luminosity in the hydrogen lines is empirically found to be proportional to the accretion luminosity (Muzerolle et al. 1998, Salyk et al. 2013,Rigliaco et al. 2015, Alcalá et al. 2017).
- This provides a measure of L_{acc} and, when combined with L_{bol}, the fraction of the luminosity from accretion.
- Using an estimate of the mass/radius ratio of the protostar and the fraction of energy radiated, L_{acc} can be used to find the mass accretion rate.
- Here we used hydrogen lines detected in near-IR spectra form IRTF/SpeX.

Sample: the protostars were chosen from the HOPS catalog (Furlan et al. 2016)[1]. This survey determined the spectral energy distributions of 330 protostars in the Orion A & B clouds.

- We initially studied 29 protostars selected from the survey for their brightness at 0.8-2.5 µm, allowing detection with IRTF/SpeX at these wavelengths.
- Fourteen have detection in two or more hydrogen lines.
- From the SEDs of the 14 protostars: two are Class I protostars, 11 are Flat Spectrum, and one is a Class II object with a residual envelope.
- HST imaging of 12/14 show eight have pointlike morphologies (no scattered light nebula), one has a unipolar cavity, and three are irregulars (Habel et al. in prep).

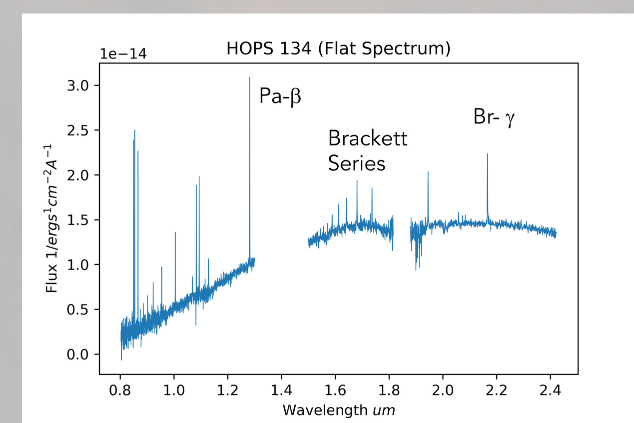
References

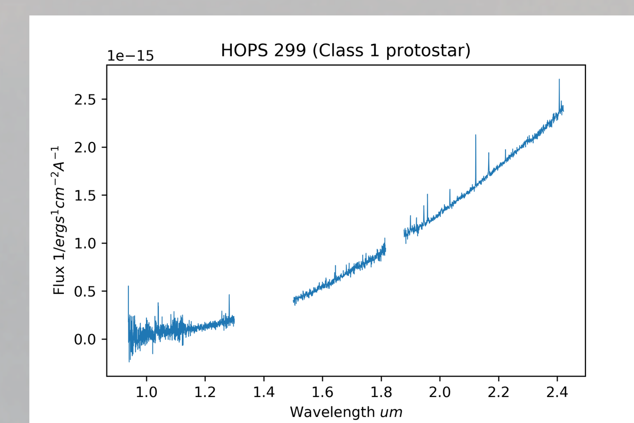
Alcalá et al. 2017 A&A, 600, A20
Cushing et al. 2004, PASP 116, 362
Draine 1989, Infrared Spectroscopy in Astronomy, Proceedings of the 22nd Eslab Symposium, p.93
Fischer et al. 2017 ApJ 840, 69
Furlan et al. 2016 ApJS 224, 5.
Hartmann et al. 2016 AARA 54, 135.
Kwan & Fischer 2011 MNRAS 411, 2383.
Muzerolle et al. 1998, AJ, 116, 2695
Rayner et al. 2003, PASP 115, 362
Rigliaco et al. 2015, ApJ, 801, 31
Salyk et al. 2013, ApJ, 769, 21

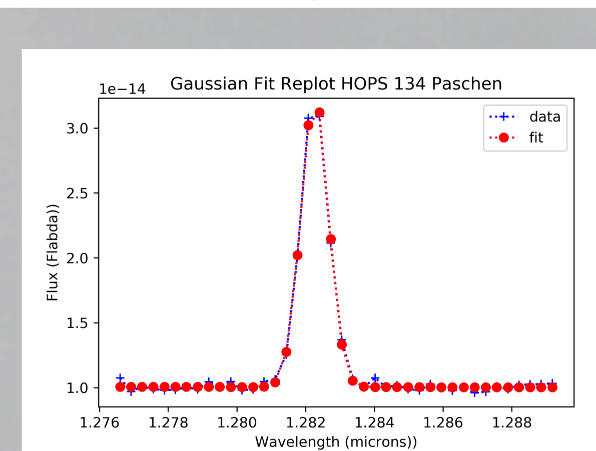
The HOPS survey data can be found at IRSA: https://irsa.ipac.caltech.edu/data/Herschel/HOPS/overview.html

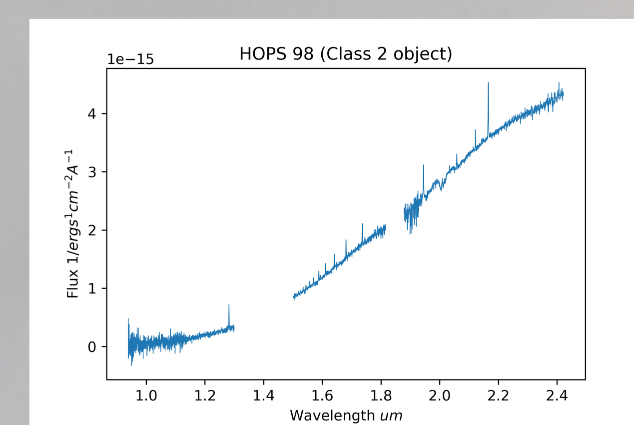
IRTF/SpeX Spectra and Line Fits

QR code for sample spectral analysis Python code









The spectra were obtained in the SXD mode of SpeX on the IRTF (Rayner et al. 2003), and reduced with Spextool (Cusing et al. 2004).

The hydrogen lines were identified and fit by a custom Python code.

Left: three example 0.8-2.5 µm spectra from IRTF/SpeX. These examples show the full range of hydrogen line intensities.

Bottom left: example fit of Pa-β line is given for HOPS 134.

Determining Accretion Luminosities from Hydrogen Line Emission

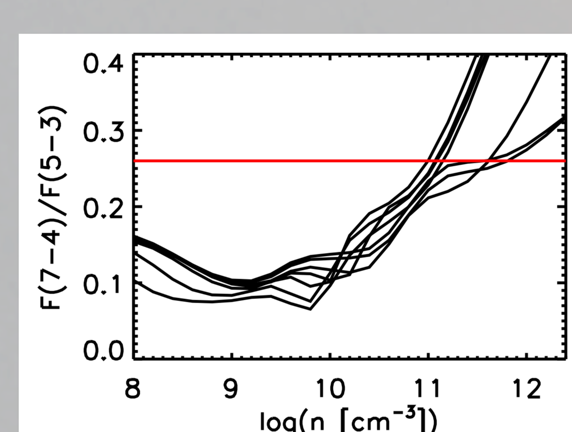
We use hydrogen lines emission fluxes to measure L_{acc} using the following procedure:

- To determine L_{acc}, we first measure the luminosity in the Br-γ (7-4) hydrogen line.
- This requires a measurement of the extinction to the accretion column. We use two hydrogen lines and the following equation to determine the extinction in the Br-γ line. This adopts the reddening law of Draine (1989).

$$\frac{F_{obs}^{\lambda 1}}{F_{obs}^{\lambda 2}} = \frac{F_{int}^{\lambda 1}}{F_{int}^{\lambda 2}} e^{-\left(\frac{\lambda_1}{2.166}^{-1.75} - \frac{\lambda_2}{2.166}^{-1.75}\right)\tau_{2.166}} \Rightarrow \tau_{2.166} = \frac{\ln\left(\frac{F_{int}^{\lambda 1}/F_{int}^{\lambda 2}}{F_{obs}^{\lambda 1}/F_{obs}^{\lambda 2}}\right)}{\left(\frac{\lambda_1}{2.166}^{-1.75} - \frac{\lambda_2}{2.166}^{-1.75}\right)}$$

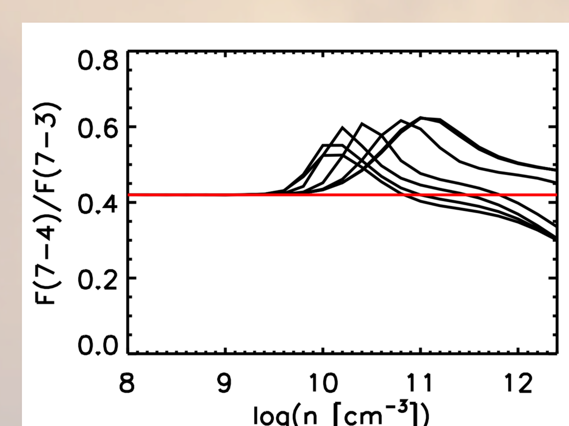
where F_{int} are the intrinsic (unabsorbed) fluxes and F_{obs} are the observed fluxes.

- Two protostars, HOPS 134 & HOPS 70, are detected in the 7-4 and 7-3 hydrogen lines (see HOPS 134 spectrum above). We use the predicted ratio of those lines from Kwan & Fischer (2011, see figures below) to estimate the extinction, $\tau_{2.166}$. These transitions were chosen for the weak density and temperature dependence of their ratio.
- We then use $\tau_{2.166}$ to determine the dereddened flux ratio of 7-4 (Br-γ) and 5-3 (Pa-β) lines for these two protostars. The average of these values is used for the intrinsic flux ratio of the Br-γ and Pa-β lines.
- We use the observed 7-4/5-3 flux ratio to determine the extinction to the 14 protostars with detections in both the Pa-β and Br-γ lines.
- The extinction values and the distance of 420 pc are then used to determine the luminosity in the Br-γ line.
- We used the empirical relationship from Muzerolle et al. (1998) to convert the Br-γ luminosity into L_{acc}
- Using an adopted mass to radius ratio of 0.25 (solar units), we determine the mass accretion rate, $\dot{M}$.



Model hydrogen line ratios as a function of hydrogen density. These are shown for kinetic temperatures between 3750 K and 15000 K and are from Kwan & Fischer (2011). The red lines show the adopted line ratios for our current analysis.

Model results can be found on the website: http://www.stsci.edu/~wfischer/line_models.html



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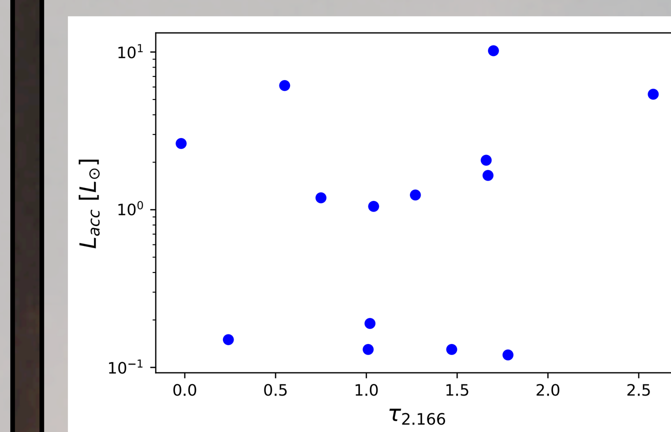
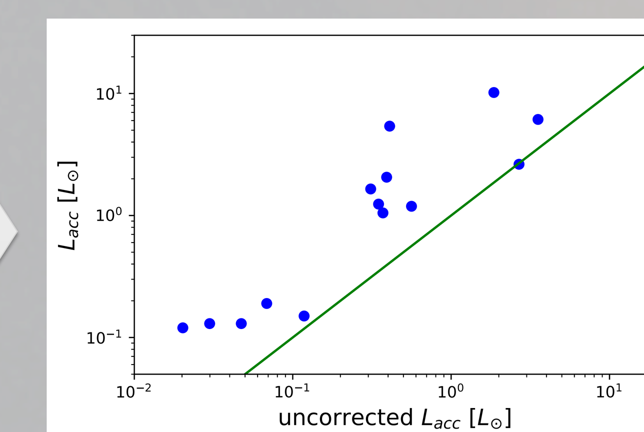
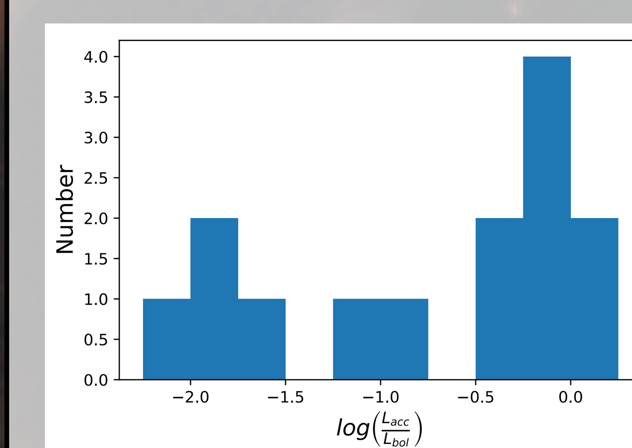
Result: *a broad range of mass accretion luminosities and rates*



L_{acc} vs estimated extinction $\tau_{2.166}$. These show a range of extinction values and no correlation with L_{acc}, confirming there is no systematic bias due to the extinction correction.

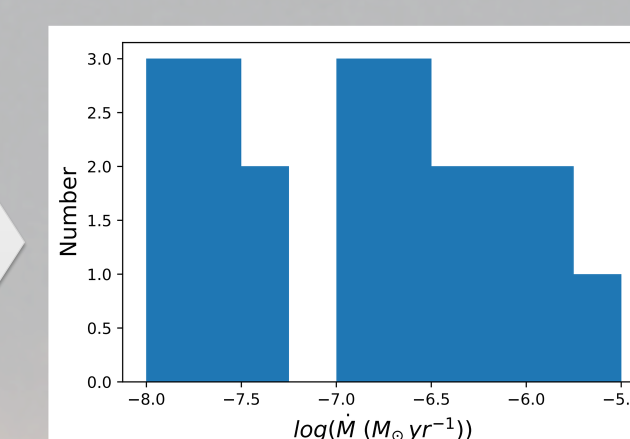
L_{acc} before and after correction for extinction. As expected, there is a correlation, but the extinction correction can change the L_{acc} by an order of magnitude.



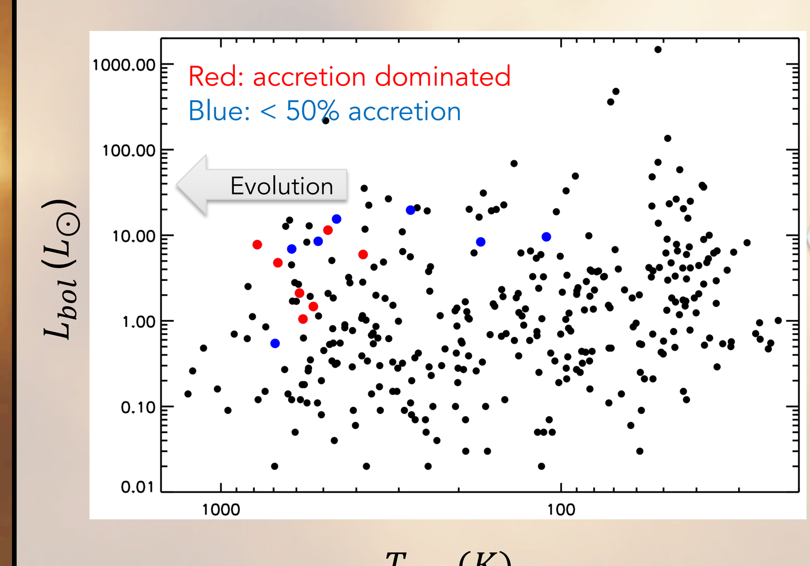


L_{acc} to L_{bol} ratios. L_{bol} estimated from the SEDs by Furlan et al. (2016). The 7/14 sources with $log(L_{acc}/L_{bol})$ values of < -0.3 have less than half of their luminosity from accretion.

Mass accretion rates. These are estimated from L_{acc}. The rates span the range from those expected for protostars (-5.5) to those typical for more evolved pre-ms stars (-8).



Discussion: Fischer et al. (2017) shows L_{bol} vs T_{bol} diagram of HOPS protostars. They proposed that the luminosities of young Class 0 protostars (T_{bol} < 70 K) are accretion dominated while more evolved protostars are increasingly dominated by their intrinsic luminosities. They predict the ratio of L_{acc}/ L_{bol} should decrease.



Location of accretion dominated protostars in L_{bol} vs T_{bol} diagram. We find 7/14 are accretion dominated. Surprisingly, these are found among the more evolved protostars, and show lower L_{bol} than those dominated by their intrinsic luminosities. No clear trend is seen.

Future directions and caveats: we have not yet corrected for potential light scattering by the envelopes, this will be done with models. Furthermore the SEDs and SpeX data are from different epochs, and variability may affect the luminosity ratios. We are now using 2-5 µm SpeX LXD mode spectra to study more embedded protostars. Ultimately, spectrographs on larger ground-based telescopes and JWST will be needed to expand the sample to younger as well as lower luminosity protostars to understand the evolution of L_{acc} and of L_{acc}/L_{bol}.