Summary

We propose a near-IR investigation of protostars with implications for the amount of material available to build planets and the timescale of planet formation. Protostars are the earliest stage of stellar evolution, where the collapse of molecular cloud fragments leads to the formation of accreting, hydrostatically supported protostars enshrouded in infalling envelopes. Due to the angular momentum of the envelopes, accretion disks form. These disks collect the infalling gas and supply it to the protostars. In these dusty disks, the onset of planetary formation begins with the growth of grains, or perhaps in more massive disks, with gravitational instabilities.

ALMA observations show the presence of disks around protostars as well as surprising levels of structure in those disks. Gaps and holes in the distribution of mm to cm sized grains may be due to the presence of forming planets. In these disks, there is a continual depletion of mass via accretion onto the stars balanced by the influx of new material via mass infall. During the later phases of protostellar evolution, accretion rates decline to the point that the disks are no longer merely funneling mass onto the protostars, and planetary system can form without being accreted. This late protostellar phase is important for setting the "initial" conditions of planet formation, i.e. the amount of mass available and the inventory of materials present.

Just as the properties of the host stars are important for interpreting observations of exoplanets, the properties of the protostars are essential for understanding the early evolution of disks and the boundary conditions for planet formation. A program of near-IR spectroscopy of protostars has been carried out using medium to high dispersion spectrographs on 4-8 meter telescopes. This program uses a well characterized sample of protostars from a decade of surveys with Spitzer, Herschel and Hubble. Using the near-IR data, we can measure the spectral types and accretion rates of nearby protostars in Orion, Perseus and other clouds. Focusing on protostars in the later stages of their evolution, we hope to achieve the following goals:

I. Refine the timescale of planet formation: the ages of young stars used to measure the timescales for disk evolution rely on models of pre-main sequence contraction, all of which assume an initial radii for contraction. Using spectral types from near-IR spectroscopy - in combination with existing measurements of bolometric luminosity and measurements of the accretion luminosity (below) - we will determine the radii of late phase protostars near the onset of pre-main sequence contraction. These radii will be our best empirical determination of the "initial" contraction radii for the subsequent pre-main sequence evolution, and can resolve one of the major uncertainties in the ages of young stars.

II. Determine the distribution of mass accretion rates: the rate of mass accretion gives a measure of how quickly disks are being depleted - this cannot be measured with ALMA. Near-IR hydrogen lines are produced in accretion flows along magnetic field lines from the disks to the protostars. By measuring the luminosities of these lines, we will measure the luminosity generated by accretion, and infer the rate at which mass flows from the disks to the protostars. We will also measure the fraction of time protostars are found in high accretion outbursts.

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1. Protostars and the Formation of Exoplanets

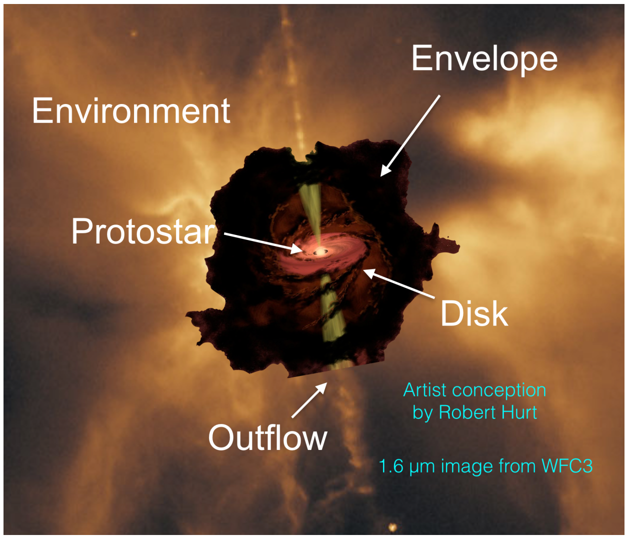

Figure 1: HST image of a protostar with a cartoon schematic of the standard picture of protostars overlaid. The schematic illustrates the basic components: the infalling envelope, the accretion disk, the central, hydrostatically supported protostar and the bipolar outflow. This proposal focuses on the properties of the

Just as the properties of host stars are an essential input into interpreting observations of exoplanets, a similarly detailed understanding of the evolution of protostars is an essential input into models of the formation and early evolution of disks, the onset of planet formation, and the early evolution of planets.

The connection between protostars and planet formation was established over 30 years ago and has remained a fundamental component of our picture for the formation of a low-mass star, (e.g. [1]). In this picture, the collapse of a molecular cloud fragment leads to the formation of a hydrostatically supported protostar surrounded by an infalling envelope. The dusty envelope hides the protostar and reprocesses the luminosity into mid and far-IR radiation. Due to the angular momentum of the envelope gas, the collapse leads to the formation of a growing, centrifugally supported accretion disk. The infalling mass from the envelope lands on the central disk, where it is transported to the inner disk and accreted onto the central protostar via magnetic fields. For mass accretion to occur, angular momentum is carried away by an accretion driven wind and/or jet launched from the disk and star. Thus **infall** supplies the disk with mass, **accretion** supplies the star with mass, and **accretion** and **winds** and deplete the disk of mass. The disk serves as a conduit of matter from the ISM, sending many times the disk mass to the central star over the lifetime of the protostar until accretion slows or stops, setting the stage for planets (Fig. 1).

Recent work has argued that the planet formation starts in the protostellar phase. The detection of gaps in the disks of the late-stage protostar such as HL Tau ([2], [32]) suggests planet formation starts in the protostellar phase ([3]), although there are multiple interpretations of the gaps (e.g. [4]). By comparing dust masses in disks to those in planets, [5] argue that the higher dust masses available in the disks of protostars (as compared to the dust masses of disks around more evolved pre-main sequence, or pre-ms, stars) may be required to form the average planetary system via core accretion. The later stages of protostellar evolution (Fig. 2) may also be the most favorable time for forming giant planets in the outer regions of disks via gravitational instabilities ([6],[7]). The continual infall of envelope gas onto disks, the accretion flow from the disks to the stars, and the fluctuating luminosity of the central stars are the *boundary conditions* of planet formation in

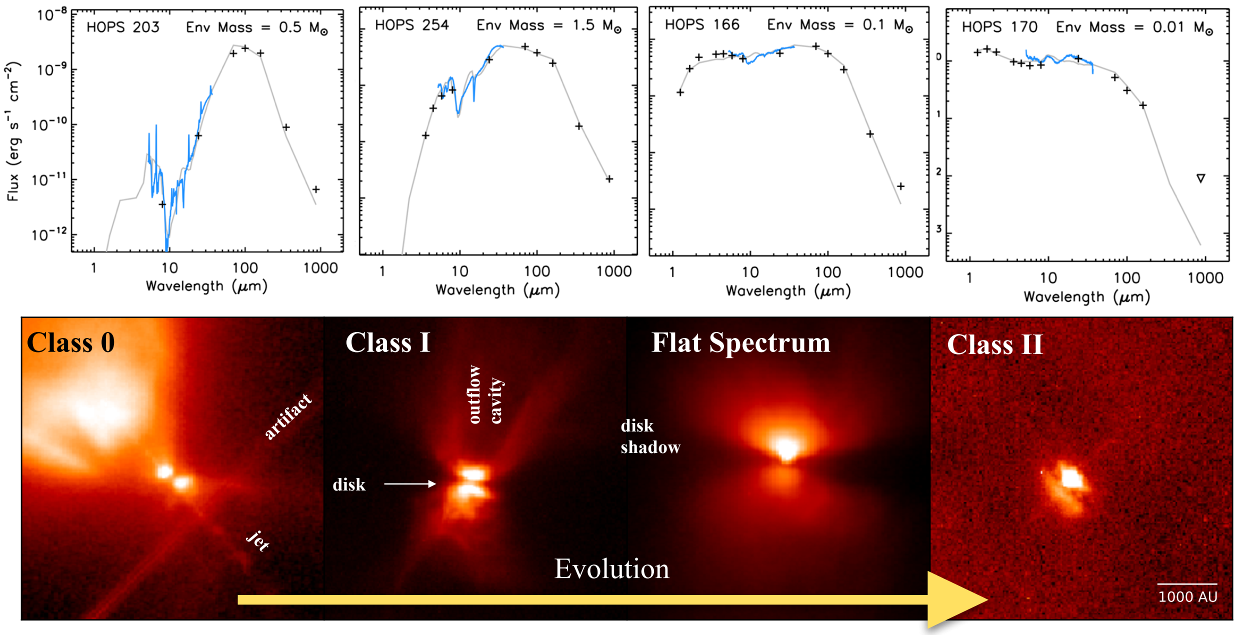

Figure 2. Top: spectral energy distributions (SEDs) from 2MASS, Spitzer and Herschel data for a Class 0 protostar, a Class I protostar, a flat spectrum protostar (a late-stage protostar with a thin envelope), and a Class II object (a pre-ms star with disk). These show the evolution of SEDs as the envelope is depleted. The "+" are photometry, blue lines are IRS spectra, black lines are models ([8]). **Bottom:** Orion protostars imaged by HST/WFC3 at 1.6 µm. Light from the central protostars are scattered by dust grains in the envelopes, the walls of outflow cavities, and in disks ([9]). The SEDs are for protostars with intermediate inclination angles (which are more common) while the protostars in the images have a close to edge-on inclination. Late-stage protostars include most flat spectrum and some Class I protostars.

the protostellar phase. Furthermore, the evolving properties of the central protostars are essential for calibrating and validating models of pre-ms star contraction used to measure planet formation timescales. This timescale sets another *boundary condition* for planet formation.

This proposal will fund the analysis of an extraordinary collection of near-IR spectra to directly measure these boundary conditions for an ensemble of protostars. They detect accretion onto protostars and measure the temperatures and radii of the photospheres of the protostars. The spectra are our primary means of exploring accretion and the central protostar itself, detecting photons from both hot gas in accretion flows and the photosphere. We focus on three questions:

1.) What is the evolution of accretion over the 0.5 Myr protostellar phase? Recent studies (see Sec 2.1, Figs 2, 3 & 4) show that the rate of mass infall onto disks decreases rapidly over the evolution of protostars (personal com.). Studies also find a decrease in the luminosities of protostars which can be explained by a concomitant decline in the rate of mass accretion from the disks onto the central protostars [24]. This decrease of mass infall and accretion mediates the evolution of disk masses ([10]) and allows planetary systems to form without being accreted.

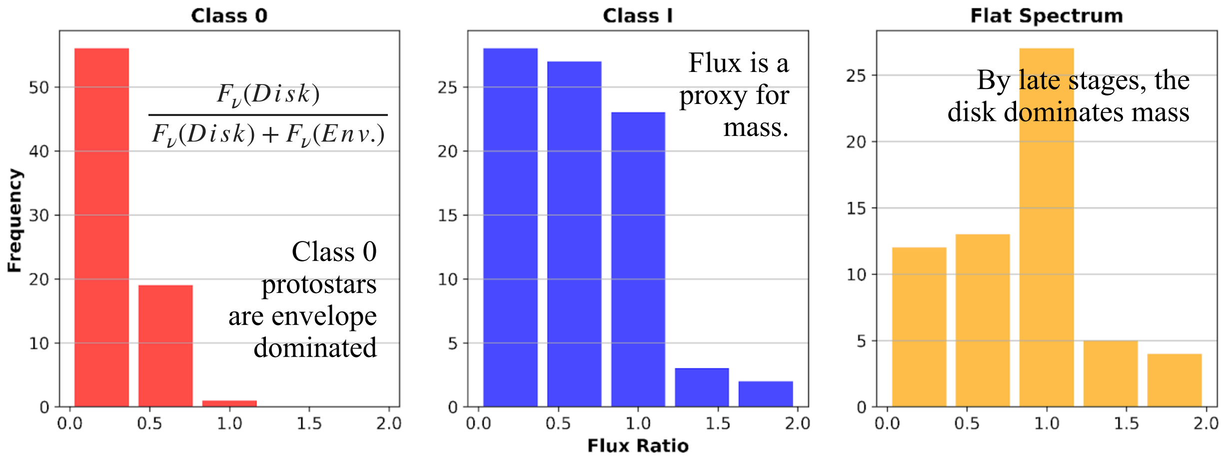

Figure 3. By the late stages of protostellar evolution, the disk sub-mm flux (a proxy for mass) dominates the total flux of the disk and envelope. Thus, only a residual envelope appears to be left. Above: ratio of ALMA 12 meter disk flux to the ACA disk + envelope flux as a function of SED class (Fig. 2) for three hundred Orion protostar (Personal. Com.). Here the flux is measured in the inner 2500 au around the protostar and includes the inner envelope. While Class 0 protostars are envelope dominated, the fluxes of some of the Class I and many of the flat spectrum protostars are disk dominated. These protostars, our focus, are near the end of stellar mass accretion but still have significant amounts of gas for feeding disks.

Direct measurements of the rate of mass accretion are needed to confirm the decline and quantify the rate of accretion during the later stages of protostellar evolution.

2.) How much does mass accretion fluctuate during the secular decline? The decline in accretion is thought to be punctuated by episodes of rapid accretion detected as bursts of high luminosity. These may occur as frequently as every 1000 years, but with a rapidly decreasing rate with evolution ([11], [62], Sec 2.2). With accretion rates reaching as high as 10^{-4} $M_\odot$ yr^{-1}, bursts can rapidly deplete disks of their mass, lowering the amount of mass available to form planets. In the late stages of protostellar evolution, this depleted mass may not be replenished. Furthermore, the heating due to the luminous bursts can influence the chemistry and mineralogy of envelopes and disks, thereby altering the inventory of material available for planet formation, and shifting the location of snow-lines in disks outward ([12], [13], [14], [15], [16], [17]). *Direct identification of outbursting protostars can constraint the duty cycle (rate $\times$ duration) and amplitude of bursts, and thus their potential effect on disks.*

3.) What are the initial radii of contracting pre-main sequence stars and how do they depend on accretion? The radius of the central protostar at the end of the protostellar phase sets the initial radius for the ensuing pre-ms contraction, and observational measurements of these initial radii are essential for using the ages of pre-main sequence stars as chronometers for disk evolution and planet formation ([18]). Large isochronal age spreads are observed in the HR diagrams of pre-ms stars ([19]). If real, the spreads imply that star formation accelerates over 10 Myr in molecular clouds ([20]). The ages depend, however, on the initial contraction radii, and

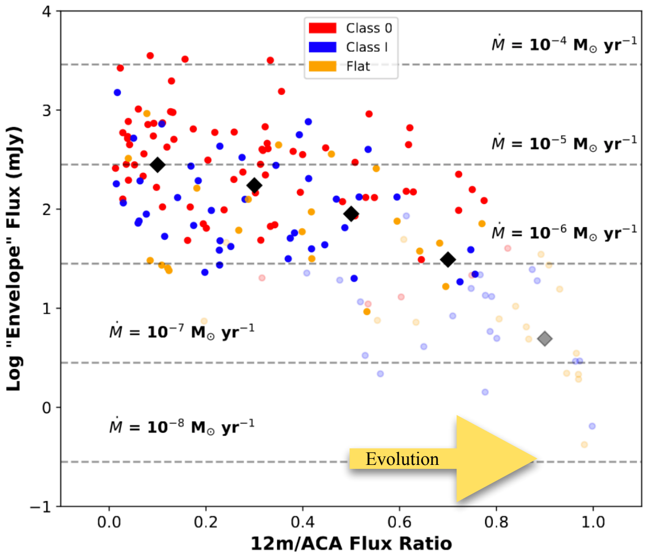

Figure 4. Envelope fluxes (a proxy for total gas and dust mass) measured with the ALMA ACA array vs the flux ratio defined in Fig. 3. The steep decline suggest that by the time the flux ratio = 0.5, the protostars are transitioning from envelope to disk dominated objects, and most of the mass is accreted. Thus the later stages that are the focus of this proposal are mostly disk dominated with low infall rates, a stage primarily relevant for setting the properties of the disks and the initial conditions of planet formation. The diamonds give median values, and the dashed lines the implied infall rates assuming a total gas+star mass of 0.25 $M_{\odot}$. (Personal Com.)

models do not provide a consensus on the radii, whether or not the radii are primarily a function of stellar mass, or whether they also reflect the accretion history ([21], [42]). T*he resolution of this puzzle has broad significance since the uncertainty in pre-ms ages impacts our estimates of the timescales for disk evolution and the time available for planet formation (e.g. [22]).*

This proposal will fund the analysis of existing data from near-IR spectrographs taken on 3-8 meter telescopes of protostars in Orion and other nearby molecular clouds. These include data from immersion grating spectrometers with R~37,500 to 45,000 that detect, in many cases for the first time, faint photospheric absorption lines. Since deeply embedded young protostars are too faint for near-IR spectroscopy, these spectra sample the later stages of protostellar evolution, when protostars have accreted most of their mass and are transitioning to pre-ms stars.

Our program uses protostars first identified with Spitzer and then characterized with Hubble, Herschel, WISE and ground-based telescopes as part of the Herschel Orion Protostar Survey (HOPS, [8]), as well as protostars found by the c2d program ([23]). Although the existing data from the NASA missions can determine the luminosities of the protostars and the properties of their envelopes, near-IR spectroscopy is the only means by which we can detect accretion flows, measure the rate of accretion, identify young protostars undergoing bursts, and directly determine the effective temperatures, intrinsic luminosities, and radii of the central protostars.

These data will provide the essential boundary conditions needed for understanding the origins of exoplanetary systems. This study will apply techniques that will be extended to fainter protostars by near-IR spectroscopy from 8 meter and ELT telescopes, and longer wavelength observations with JWST. The data will address the NASA strategic objective to “Understand The Sun, Earth, Solar System, And Universe” and the NASA Cosmic Origin goal of understanding “How did the universe originate and evolve to produce the galaxies, stars and planets we see

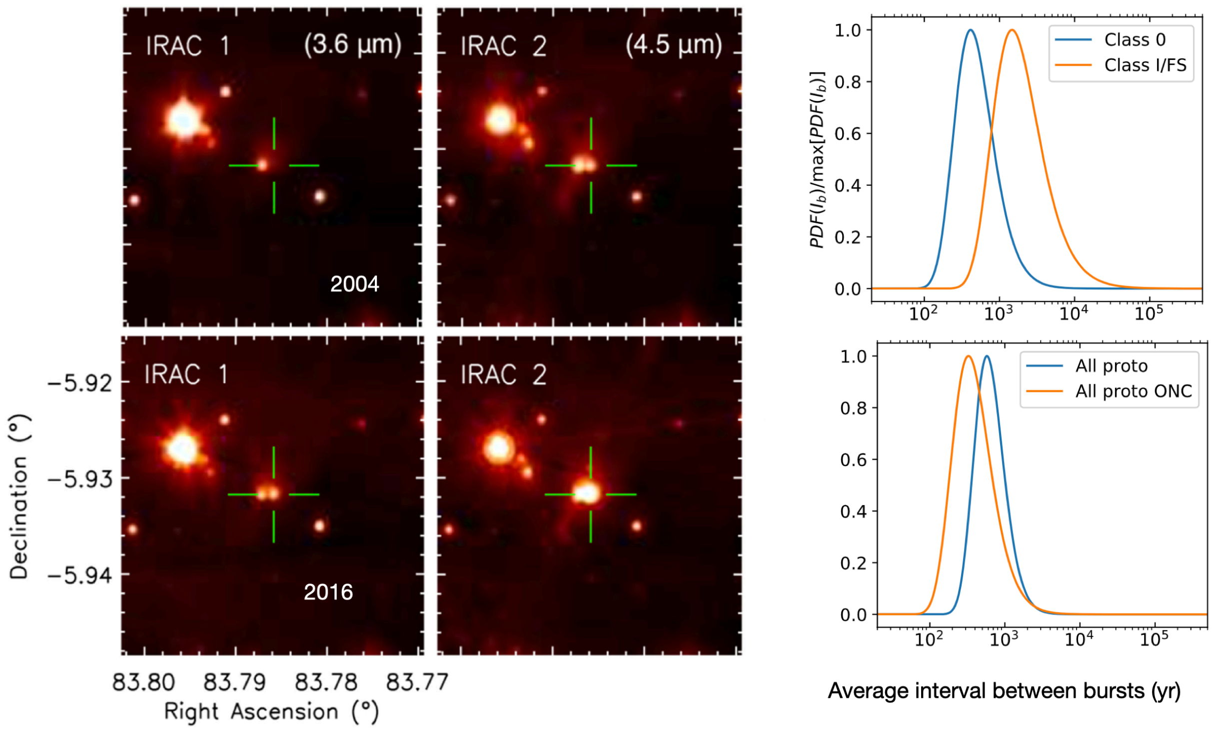

Figure 5. Left: outbursts of the HOPS 12 and 124 Class 0 protostars detected by Spitzer in the 3.6 (IRAC 1) and 4.5 µm (IRAC 2) bands [62]. The objects are shown before (2004) and after the outbursts (2016). **Right: p**osterior PDFs of burst rates estimated from the number of Orion protostars caught outbursting. Although the average interval between bursts is ~1000 years, the value increases with evolution. The interval is ~440 yr for Class 0 protostars, and appears to decrease to ~1700 years for more evolved protostars, although with large uncertainties [62]. No outburst has been detected to date in a disk dominated protostar, suggesting that the rate may be quite slow for the most evolved protostars that are the focus of this proposal (personal com.)

today?" *Finally, the techniques deployed and tested here will provide a basic tool kit for observing accretion onto forming planets in the forthcoming decade* (e.g. [25], [26]).

2. Building on the Spitzer, Herschel and Hubble Protostar Survey

Protostars radiate broadly across the infrared, from 1.6-500 µm, and space observatories are essential for their study. Spitzer, Herschel, and Hubble provided well sampled spectral energy distributions (SEDs) and high spatial resolution (40 au) images of protostars in nearby clouds (Fig. 2). The Herschel Orion Protostar Survey obtained 1.6-870 µm SEDs for 330 protostars in the Orion molecular clouds (e.g. [8]). Hubble 1.6 µm images were obtained for 307 of the Orion protostars (e.g. [27], [28]). The c2d program obtained SEDs of protostars in the Chameleon, Ophiuchus, Perseus, and Aquila clouds, at distances of 140 to 440 pc ([23], [29]), and subsequent HST programs provide high resolution images. In this section, we summarize the relevant results from these surveys and elaborate on how near-IR spectroscopy will expand our understanding of the evolution of disks during the protostellar phase.

2.1 Measuring the Secular Evolution of Mass Accretion

Infall from an envelope supplies mass to the central star/disk system which can then be accreted onto the central protostar. Mass infall occurs over a free fall time (several hundred thousand years), and the rate of infall sets a time averaged rate of mass accretion onto the central protostar. Measuring the evolution of infall can distinguish between models invoking different physical processes for controlling infall (e.g. [30]). In Figs 3 and 4, we show the evolution of envelopes by comparing the ratio of the ALMA measured disk fluxes (measured with the high resolution 12 meter array) to the total envelope and disk fluxes (measured with the low resolution ACA array). The sub-mm fluxes are an approximate proxy for mass. These data show rapid dissipation of the protostellar envelopes, with many of the late stage protostars that are the focus of this work with low infall rates and dominated by their disks (Fig. 4). This decrease in infall appears to be accompanied by a decrease in luminosity. [24] found a systematic decrease in luminosity with evolution, with envelope dominated Class 0 protostars having higher luminosities than more evolved, disk dominated Class I and flat spectrum protostars ([24]). This all points to the rapid evolution of protostars over their 500,000 years lifespan, with a rapidly thinning envelope and decreasing accretion rates. For many of the late stage protostars targeted by this proposal, the assembly of the stellar mass is largely over, and infall primarily feeds the growth of a disk.

The masses of protostellar disks are set by a competition between the infall of mass onto the disks and the loss of mass from the disks via accretion of gas onto the protostars or through accretion driven winds ([31]). [10] found that disk masses of the Orion protostars evolve with age, with the median dust masses decreasing from 38 $M_\oplus$ to 14 $M_\oplus$ (and the implied gas masses decreasing from 0.01 $M_\odot$ to 0.004 $M_\odot$) as the protostars evolve from Class 0 to late-stage flat spectrum protostars over a 0.5 Myr time period. If we assume that mass-gain by infall and mass-loss by winds and accretion are nearly in balance [24], the decline in infall will lead to a decline in accretion rates. When the accretion rates eventually drop below 10^{-7} $M_\odot$ yr^{-1} (Fig. 4), the disk depletion time ($M_{disk}/\dot{M}_{acc}$) exceeds the 0.17 Myr duration of the flat spectrum phase ([14]). At this point, disks no longer function as conduits of mass flow from the envelopes to the protostars, and planetary systems can begin to form without being accreted. The disks at this time are still sufficiently massive to produce the masses of observed planetary systems [7]. In comparison, the disks of older pre-ms stars in Orion have systematically lower masses and are insufficiently massive enough to produce observed planetary systems, perhaps because they are already depleted for planet formation [33]. Hence, *the decline in infall/accretion sets the masses of disks at the end of the protostellar phase, and consequently the masses of planetary systems.*

Measuring the accretion rates of late stage protostars is difficult since their total luminosities are likely dominated by their intrinsic luminosities, and not accretion. Thus, an independent measure of accretion, besides the total luminosity of the protostar, is required. *This proposal will test the declining accretion rates proposed by [24] by directly detecting accretion flows with near-IR spectroscopy and measuring the accretion luminosities of late stage protostars.*

2.2 Characterizing Episodic Accretion onto Protostars

The slow, secular decline in accretion onto protostars is punctuated by bursts of rapid accretion (Fig. 5). These episodes of rapid accretion are thought to result when the rate of infall onto the disk exceeds the rate of accretion of gas from the disk onto the star. The resulting growth in disk mass leads to instabilities that trigger episodes of high accretion and luminosity as the disk mass is dumped onto the central protostar. These triggers may be gravitational or thermal instabilities (e.g. [36], [37]); the thermal instabilities may in turn be triggered by the presence of a young planet inhibiting the flow of material into the inner disk ([38]). The rapid accretion rates implied by the luminosities of outbursting protostars, as high as 10^{-4} $M_{\odot}$ yr^{-1}, can rapidly deplete disks of their mass, lowering the amount of mass available to form planets. The heating by the bursts can also desorb ices into the gas phase ([13]), shift the ice lines in disks ([15], [16]), and process dust material ([12]); thereby altering the chemical/mineralogical inventory of available material.

To measure the rate of bright protostellar outbursts in the Orion molecular cloud, [62] compared multi-epoch Spitzer photometry of all the protostars in the HOPS sample. They found five outbursts where the luminosity increased by more than a factor of five. Three of these are Class 0 protostars, which make up roughly a third of all protostars ([35]). The other two are later stage Class I and flat spectrum protostars ([34]). These results are consistent with every protostar undergoing an outburst every ~1000 years, with the accretion rate increasing by a factor > 5 during bursts. However, they also suggest that the rate of bursts is declining, with a bursts every ~440 years for Class 0 protostars, and every ~1700 years for older protostars. Furthermore, both of the later stage protostars with bursts are still envelope dominated (personal com.); to date, no outburst have been detected in the Orion A or B clouds from a disk dominated protostar.

Motivated by the uncertain rate for later stage protostars, we will provide an alternative constraint on bursts. By measuring accretion luminosities using near-IR hydrogen lines and by identifying protostars with the spectral signatures of FU Ori bursts, this program will measure the distribution of accretion rates during bursts and the fraction of time (i.e. the duty cycle) spent in bursts for late stage protostars. Using estimates of the rate of bursts, and given that the fraction = rate × duration, this fraction will place the first constraints on the duration of bursts.

In total, by building an accurate picture of mass accretion for late-stage protostars, with a direct observational accounting of the rate at which accretion depletes disks and bursts process the disk material, we will be taking an essential step toward understanding how accretion processes shape the reservoir of material available for planet formation.

2.3 Protostellar Radii, Ages of Young Stars and the Time Evolution of Disks

Since the positions of pre-ms stars in the HR diagram is the best method for measuring the ages of young (< 5 Myr) stars with gas rich disks, a deep understanding of the factors that determine their location in the HR diagram as a function of their age is essential for using young stars as chronometers for disk evolution and planet formation (e.g. [18]). The ages come from the comparison of the positions of pre-ms stars in the HR diagram with model evolution tracks. An essential input into the models is the location of the protostar at the onset of contraction and pre-ms phase. Since this location depends on the physics of protostellar evolution, not pre-ms evolution, this location is often assumed; and the ages of stars for the first few million years can be affected by this assumption. [39] defined the s*tellar birthline* as the location of stars on the HR diagram at the end of their protostellar phase and the beginning of their pre-ms phase. The location of the birthline is effectively a mass vs radius relationship; i.e. for a given mass, the radius of a protostar at the onset of pre-ms contraction. This location depends on the uncertain details of mass accretion: the initial mass and radius of the protostar, how much of the energy gained by mass accretion is immediately radiated back into space, the rate of deuterium burning, and the rate at which deuterium is replenished by accretion (e.g. [40], [41], [42]).

Varying these factors in models may lead to a spread in the birthline, with different protostars of the same mass starting their contractions from different locations in the HR diagram. [43], [44] modeled the observed spreads in isochronal ages combining variations in the the initial masses and radii of the model protostars, variations in the amount of accretion energy radiated back into space, and time variable accretion. The resulting spreads in initial radii for the ensuing pre-ms stars would be misinterpreted as an age spread. On the other hand, models by [42] predict a much smaller scatter due to different accretion physics. *Where models bring no consensus, observations are required*. Direct measurements of protostars are needed to measure the initial radii, thus determining the initial condition for contraction. They are also needed to determine whether a narrow birthline is present, making individual age estimates possible, or whether the radii are widely scattered. In the later case, ages of young stars from HR diagrams may be intrinsically limited by the initial scatter and must be interrupted skeptically.

This proposal will provide the most extensive and robust measurements of the locations of young stars at the onset of pre-ms construction to date. We will measure the T_{eff} and radii of protostars with our near-IR spectra. By focusing on late stage protostars accessible to the near-IR, we will measure these properties near the onset of the pre-ms phase. These data will empirically define the initial conditions of pre-ms contraction, test competing models, and resolve a major uncertainty in using pre-ms tracks to measure disk lifetimes.

3. Near-IR Spectroscopy of Nearby (< 500 pc) Protostars

Current surveys of protostars focused primarily on observations of envelopes, disks and outflows in the mid-IR, far-IR, sub-mm, and millimeter regimes, and they only indirectly constrain the properties of the central protostars. At mid and far-IR wavelengths, the reprocessed radiation from the dusty disks and envelopes surrounding these protostars dominate the SED and submerge any emission from the protostar itself. In contrast, at near-IR wavelengths (λ <2.5 μm), the photosphere provides a significant, if not dominant, fraction of the total flux. This allows the detection of photospheric absorption lines and emission lines created by accretion onto the photospheres (Sec. 3.1). In rare FU Ori outbursts, photospheric features in the inner accretion

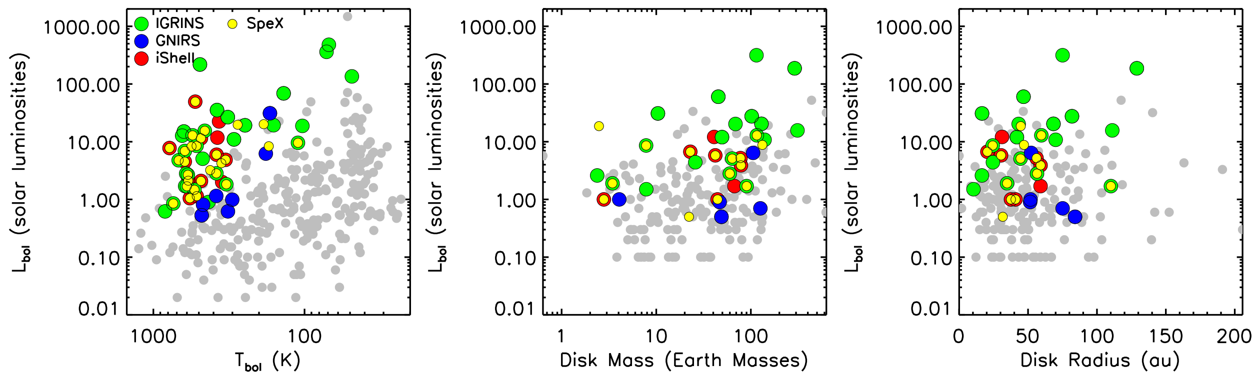

Figure 6: Left panel - Bolometric temperature vs luminosity (BLT) diagram for the Orion protostars ([24]). The protostars with near-IR spectra are displayed with the color indicating the instrument. This shows that the spectra primarily sample late-stage protostars with high bolometric temperatures. Cases where a SpeX marker is seen on top of the marker of another instrument shows that we have data from both instruments. Middle panel - ALMA disk masses vs luminosities plot for the Orion protostars with ALMA detections. The dust masses are from [10]. Right panel - deconvolved disk sizes vs luminosities. The masses of protostars with disk radii > 40 AU can be measured with kinematics observations using ALMA, ultimately allowing for observational measurements of both the protostellar radii and masses.

disk become apparent. Thus, near-IR observations have the unique ability to constrain the basic properties of the central protostars (temperature, radius, luminosity), measure the accretion luminosity, and search for protostars undergoing accretion outbursts.

This proposal will fund a study of near-IR spectroscopy of Orion protostars using recently obtained data from the IGRINS, iSHELL, and GNIRS spectrographs supplemented by data from SpeX and RIMAS (Fig. 6). The deployment of immersion grating spectrographs on 3 to 4 meter telescopes has provided new opportunity for protostar studies. The IGRINS and iSHELL spectrographs obtain R~45,000 & R~37,500, respectively, cross dispersed spectra in the H and K-bands. The IGRINS spectrograph was deployed on the Lowell Discovery Telescope (LDT) between 2016-2019. It obtains simultaneous H and K-band spectra with the sensitivity to detect narrow, veiled photospheric features in the K-band. We have access to spectra of 32 Orion protostars from IGRINS (31 from LDT and 1 from McDonald), 12 spectra of Perseus protostars (LDT), 1 spectrum of a Chameleon protostar (Gemini South) and 16 diskless pre-main sequence stars in Taurus as standards (LDT). We also have access to spectra of 20 protostars with iSHELL on the IRTF. We have reduced the IGRINS data (see next section) and iSHELL data, although improvements are still being made to the reduced spectra. In addition, we will analyze existing GNIRS/Gemini North R~5900 spectrum of seven protostars in the Orion molecular clouds; these target protostars too faint for the spectrographs on 3-4 meter telescopes.

We supplement these data with existing, reduced IRTF/SpeX near-IR spectra of 50 protostars, 29 of which show detections of the Br-γ line in emission from accretion. Although the focus is the

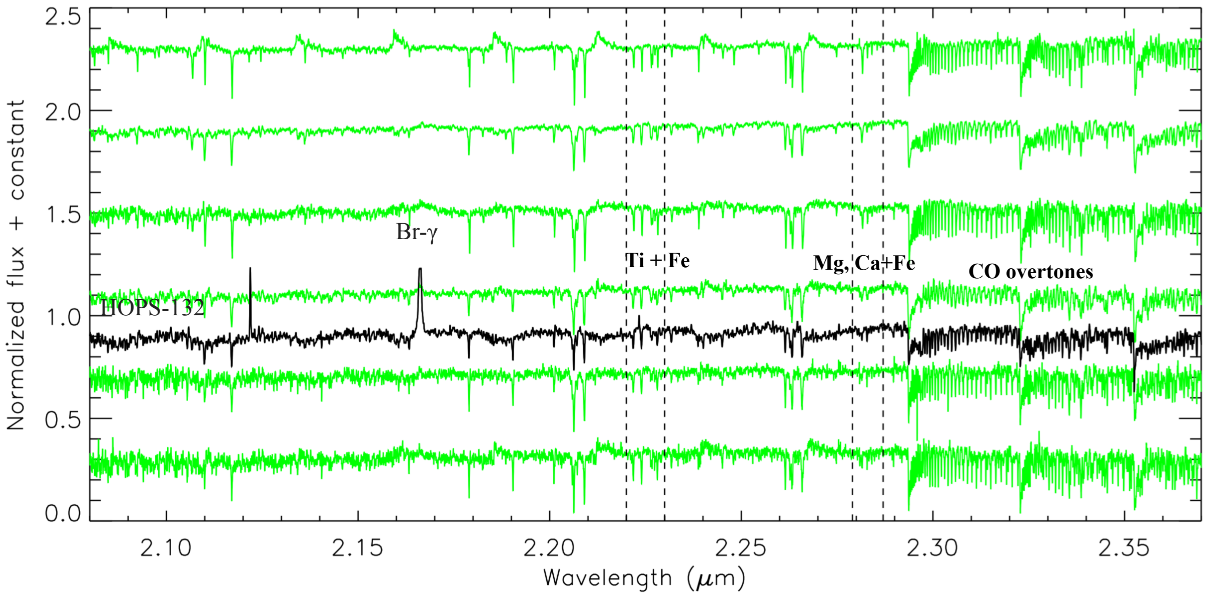

Figure 7: the IGRINS spectrum of HOPS 132 compared to a grid of IGRINS spectra of diskless pre-ms stars from Taurus ranging from K6 to M6. A constant flux density equal to 50% of the continuum has been added to the pre-ms stars to simulate the effect of veiling. The ***relative*** strengths (or ratios) of the Ti, Fe, Mg and Ca lines in the regions marked by the vertical dashed lines show a clear dependence on T_{eff}, giving a spectral type of M3 for HOPS 132. These give a veiling independent temperature. The emission lines are Br-γ and an H_2 line. The top spectrum shows artifacts due to the order merging of the cross dispersed spectra.

existing data, we will extend observations with the forthcoming RIMAS spectrograph on the LDT and potentially with the IGRINS spectrograph on the Gemini South telescope.

3.1 Determining the Veiling, Spectral Types and Radii of Protostars

Photospheric features can be detected in protostars in the near-IR, as demonstrated by [45], [46], [47] and [48]. Absorption lines of Ca, Ti, Fe, Mg, as well the CO vibrational overtones are present (Fig. 7). These lines are significantly weaker than those observed toward pre-ms or main sequence stars due to the strong veiling, a non-stellar continuum that can be several times higher than the stellar flux ([47], [48]). Veiling in the near-IR is thought to be due to a combination of thermal emission from the inner dust walls of disks (where the dust temperatures reach the sublimation temperature for silicate grains), dust in the infalling envelope, and emission from the hot gas inside the sublimation radius of the disk ([49], [50], [51]). Due to the shallowness of the heavily veiled absorption lines, high dispersion spectrographs such as IGRINS and iSHELL are necessary to detect these narrow features (Figs 7 & 8).

Our ultimate goal is to determine the radii, and to a lesser extent, masses of the protostars. We have obtained IGRINS spectra of pre-ms stars without disks (Class III objects) in Taurus with well characterized spectral types from visible light spectra. These are standards with a surface

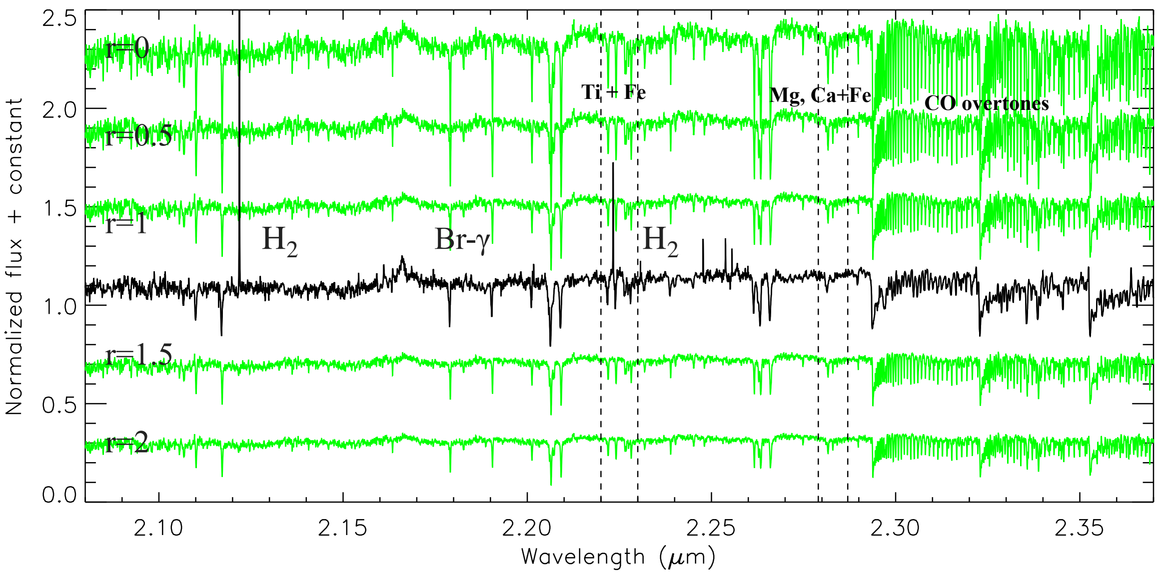

Figure 8: Gemini South IGRINS spectrum of the protostar HY Cha compared to a spectral standard from Fig. 7. A constant continuum with increasing levels is added to the standard to simulate veiling with r = 0 to 2, this protostar has an r = 1 (i.e. photosphere and veiling emission are equal). While the relative strengths of lines give temperatures, the total equivalent widths of the lines, particularly temperature insensitive lines, measure the depth of the veiling. By using lines ratios for temperatures and depths for veiling, degeneracies in the determination of these parameters can be minimized. HY Cha shows emission lines of Br-γ and H_2.

gravity between that of giants and dwarfs. In Fig. 7, we compare the 2 μm spectrum of the protostars HOPS 132 to the standards and find that the many of the features are insensitive to temperature. A comparison of the depth of these features to those in the standards provides the veiling *r*; the ratio of the veiling flux to the photospheric flux (Fig. 8, see analysis of [51]). In contrast, the ratios of temperature sensitive features allow for the measurement of the spectral types of the late K to M type stars to within two sub-classes (Fig. 7). This corresponds to 10% in T_{eff}, using standard conversions in the literature (e.g. [52]). Broadening of the lines due to rotation and Zeeman effects should not affect this analysis when standards are convolved by a kernel to simulate broadening. We will also identify rapidly rotating protostar.

The T_{eff} can be combined with luminosities to determine the radii of the protostars ($L = 4\pi R^2 \sigma T^4$) and place them on the HR diagram. The luminosities will be calculated by two independent means. We will use the total luminosities integrated over the SEDs of the protostars ([8]) and the fractional accretion luminosities determined from the hydrogen lines and veiling values (see 3.2) to subtract out the accretion luminosities. We will use the foreground reddening determined by model fits to the SEDs ([8]). Alternatively, we will apply bolometric corrections (as tabulated for pre-ms stars by [53]) to the observed near-IR photospheric fluxes, after corrections for veiling and reddening, to calculate a luminosities. Here the reddening will be extracted from the models fit to the SEDs by [8]. The contributions from scattered light will come from the analysis of the F160W HST images. Finally, comparisons of the radii and T_{eff} to pre-ms tracks will constrain the masses of the protostars. For sources with resolved disks (e.g. [10]), dynamical masses will ultimately be measured with ALMA. Ours is a different approach than that of [47], who compared Keck spectra of protostars in Serpens an Ophiuchus to models to determine T_{eff} and log(g). In comparison, our Orion sample is larger and better characterized by previous data. We will test whether we see a narrow range of radii as a function of mass, as suggested by the Serpens data of [47], or a wide range of radii, as suggested by their Ophiuchus data. Orion, due to its large size, is a more representative region for our galaxy than Ophiuchus.

Pessimistic estimates of 20% uncertainty in veiling, 40% uncertainty in luminosity and 10% uncertainties in T_{eff} result in 25% uncertainties in radii. Although this is high compared to the precision achieved for main sequence stars, it is small compared to the order of magnitude changes in radii during protostellar and pre-ms sequence evolution ([42]). HST and ALMA data will be used to identify companions down to 40 AU; however, since many companions will be at smaller distances, multiplicity will introduce further uncertainties in the luminosities. Binarity can inflate the measured radius of the primary up to 40% in the case of equal masses binaries. Furthermore, since companions contribute to the luminosity and can reduce the measured T_{eff}; they will bias the inferred radii to higher values. To account for this bias, we will simulate the effect of binaries for an adopted distribution of mass ratios; these will be informed by spectroscopic binary surveys of young stars ([61]). From this simulation, and from the other uncertainties, we will calculate the posterior distribution of radii for each protostars. We will also examine, using simple models, the effects of star spots on the determination of the temperature, the luminosity, and the radius. We note in Fig. 6 that our sample is biased towards more luminous protostars due to the limitation of current instrumentation. Nevertheless, we can assess the initial radii for a sample spanning two orders of magnitude in luminosity. Furthermore, our analysis will set the stage for observations on 8 m/ELT telescopes of fainter protostars.

This analysis will provide the most extensive, rigorous analysis of the locations of protostars in the HR diagram at the onset of pre-ms contraction. It will provide a clear test of models which predict that protostars of a given mass can have a large range in initial radii, and it will provide direct constraints on the initial radii needed as an input to pre-ms models to provide realistic ages. It will also pave the way for deeper observations on Gemini South with IGRINS.

3.2 Measuring Accretion Luminosities and Outburst Fractions

Our program will observe mass accretion onto late-stage protostars using near-IR spectroscopy, with the goal of determining the distribution functions of accretion luminosity, fraction of total luminosity from accretion, and mass accretion rates for late-stage protostars, as well as the fraction of protostars undergoing episodic accretion bursts. Protostars typically gain mass via magnetospheric accretion, where gas is funneled from the disks onto the central protostars along magnetic field lines (e.g. [54]). This process has been studied in great detail toward pre-ms stars where UV/visible radiation from the accretion shocks can be directly detected ([55]); however, the UV/visible radiation cannot be detected toward embedded young stars and protostars. In these embedded sources, infrared hydrogen lines from hot gas in the accretion flows are the best tracers of magnetospheric accretion. Velocity resolved Br-γ emission toward pre-ms stars confirms that this emission comes from infalling, not outflowing, gas ([56]). The luminosities in the Br-γ and Pa-β lines of pre-ms stars show an almost linear correlation with their accretion luminosity ([57],[58]), making these lines the best known tracer of accretion toward protostars.

Magnetospheric Accretion from IGRINS/iSHELL/GNIRS data: to measure the fractional accretion luminosity, we use the effective temperatures (T_{eff}) and veiling (r) and the formula

$$f_{acc} = \frac{\alpha}{\beta(T_{eff})} \frac{F_{Br\gamma}(r+1)}{F_{cont}(2.166\ \mu m)} \quad ,$$

where $F_{Br\gamma}$ is the Br-γ flux, $F_{cont}(2.166\ \mu\mathrm{m})$ is the continuum flux under Br-γ line, α is the empirical scale factor where $L_{acc} = \alpha\ L_{Br\gamma}$ ([58]), $\beta(T_{eff})$ is a bolometric correction, and *r* is the veiling. The ratio of the fluxes is independent of distance or extinction, and an extinction correction is not required. Once f_{acc} is determined, the value of L_{acc} can be determined from the SED derived value of L_{bol}. Although the relationship between L_{acc} and $L_{Br\gamma}$ is not exactly linear, as assumed here, the value of α can be iteratively corrected once L_{acc} is estimated to take into account the slight non-linear dependence ($L_{acc} \propto L_{Br\gamma}^{1.2}$, [58]). Finally, by using our measured radii and masses from pre-ms tracks (and ultimately, using measured masses using the keplerian rotation of disks by ALMA), these luminosities will be used to infer mass accretion rates for every IGRINS/iShell/GNIRS spectrum with a Br-γ line detection, and upper limits for those without detections. For objects with high $F_{Br\gamma}$, and hence with high accretion rates well beyond those calibrated in empirical relationships by [58], we will assume that $f_{acc} \approx 1$.

We will measure, for the first time, the distribution of accretion rates for a sample of late stage protostars. This will measure how many of these protostars have low accretion rates, as is predicted by [24] and the low infall rates (Fig. 4). We will also find whether there is a significant fraction of protostars showing rapid accretion; these could be undergoing episodic outbursts.

Extreme outbursts: although rapid accretion is evident in protostars with bright hydrogen lines (Fig. 7), the most extreme, luminous accretion events, the FU Ori outbursts or FUors, are characterized by the *lack* of near-IR hydrogen lines, as well as the presence of deep CO overtone absorption and broad spectral features due to H_2O ([34]). These characteristics are thought to result from the rapid accretion crushing the magnetic field of the young star and the disk extending itself to the stellar surface ([54]). The detection of a late-stage protostellar FUor (V2775), the realization that FUors can have luminosities under 100 $L_\odot$ ([34], [59]), and the long duration of FUors (*the* FU Ori outburst has continued over 80 years), suggests that some of the protostars in Orion may be undergoing FU Ori outbursts. To date, two FU Ori bursts have been identified in our sample: V2775 ([34]) and V883.

We will search for protostars without hydrogen lines plus deep CO and H_2O absorption. We will then apply the more stringent criteria of [48] that uses the equivalent widths of Na and Ca absorption and the depth of the CO absorption. The luminosity of the FUors is dominated by accretion, and we will use the total luminosity measured from their SEDs as the accretion luminosity of these sources. Counting both FUors and protostars with bright hydrogen-lines, we will determine the fraction of our sample in elevated, rapid accretion states.

Variable Magnetospheric Accretion with SpeX and RIMAS: a primary uncertainty is the variability of the accretion rate. To measure the typical variability of magnetospheric accretion, we will use observations made with the R~1200 IRTF/SpeX spectra of Orion protostars in the SXD mode (1-2.5 μm) or LXD mode (2-5 μm), both containing the Br-γ lines. For some protostars, these cover extend back to 2006. We will compare the Br-γ fluxes between multiple epochs of SpeX data, and to the IGRINS/iSHELL/GNIRS data. To maximize the interval over which we will measure the lines, we will also use the forthcoming RIMAS near-IR (R~6000) spectrograph on the LDT. With RIMAS, we will obtain spectra from a large fraction of our sample to compare with those taken with other instruments 5-15 years ago. We will observe selected protostars three times in a one week observing run, and repeat this twice a year in two observing runs (fall and winter), over the two years of this grant. Using this plan, these data will provide a measurement of the amplitude of variability over time intervals of days, weeks, months, years, and decades. This provides an approximately logarithmic sampling in roughly equal intervals with $\log_{10} \Delta t_{\rm days} \approx 0 - 3.7$. The measurements of the lines over this logarithmic distribution of time intervals is critical for assessing the affect of accretion variability on the distribution of accretion luminosities we extract from the IGRINS data.

Summary: T*hese data will provide the most extensive survey of magnetospheric and eruptive mass accretion in the late-stages of protostellar evolution to date. We can test whether accretion is effectively over for most protostars, and determine the fraction of disks that are still being rapidly depleted. We will assess the variability of the accretion on day to decade scales. In the context of burst models, where a quiescent low accretion state is punctuated with bursts, we will assess the duty cycle and amplitude of the bursts. These data will provide a unique snapshot of accretion toward a sample of protostars that will place direct constraints on the evolution of mass accretion and how that evolution influences the properties of disks as planets begin to form.*

4. YSOLab

To provide undergraduate students an opportunity to participate in this project, we are organizing a research group called YSOlab. In a new dedicated space for undergraduate computational research, we will assemble a team of physics and astronomy majors to work on the analysis of the spectra. Supervised by the graduate student supported by this grant and myself, the students will break into three or more sub-teams, each analyzing the same spectra and comparing results to ensure that the analyses have converged. The analyses will be done with Python scripts and documented in Jupyter notebooks. During all three years, one undergraduate will be recruited to work over the summer paid by a stipend from this grant.

5. Program Timeline and Effort

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Year 1: grad student, the co-Is, and the PI will perform the final reduction of the IGRINS data and reduce the GNIRS data. They will develop software for the analysis and test the software with the YSOlab team. As they develop the code, YSOlab teams will then start analyzing the data; testing the code for further improvements. Concurrently, we will publish one paper on the spectra of intermediate luminosity protostars in Orion; this paper will provide an initial demonstration of our methods. Over the summer, an undergraduate under the supervision the grad student will measure accretion rates from the combined data set. We will also take data with RIMAS; the PI and graduate student will staff the first run, but subsequent runs will be staffed primarily by by the graduate student and undergraduates chosen from the YSOlab team. Although people must be at the telescope, undergraduates will participate remotely at UToledo in our observing room. These data will be reduced by the graduate student with help by the summer undergraduate. Initial results will presented at a meeting.

Year 2: grad student, co-Is, and the YSOlab team will focus on the analysis of the IGRINS, iSHELL and GNIRS data. We plan to publish two papers: one on the grid of standards, and one paper on the protostars in Perseus. The summer undergraduate will continue to work on measuring accretion rates. We will continue to take and reduce data with RIMAS. The PI, Co-Is and graduate student will present results at meetings. The undergraduate will continue to work on the accretion rates.

Year 3: The final RIMAS data will be taken. Two papers on the Orion results, one on the radii of protostars and one on mass accretion rates, will be submitted. The acceptance of the paper will coincide with graduate student delivering the spectra and Jupyter notebooks to an archive. The undergraduate will present their work at a national meeting. The PI and/or Co-Is and graduate student will present the final work at meetings.

6. Data Management Plan

The primary data products will be reduced spectra. We also plan to upload all our spectra to an existing HOPS archive on IRSA, thereby providing all extent information on each Orion protostar on a single site. Although the reduction is with SpeXtool and custom software for IGRINS, we will document the analysis of each protostar with an individual Jupiter notebook. One notebook for each protostar will be archived, either with the data or on Github. These will show our best fit values and allow users to assess and modify our work, for example by using a different grid of standards.

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