The Protostellar Luminosity Function

Program contacts: Lynne Hillenbrand, Tom Greene, Paul Harvey
Scientific category: STAR FORMATION
Instruments: FORCAST, HAWC
Hours of observation: 180

Abstract

We propose mid- and far-infrared imaging observations with *SOFIA* of low bolometric temperature objects discovered through large area surveys of galactic star forming regions with *Spitzer*. The sources are not seen shortward of 8 μm down to limiting flux densities of 0.1 mJy but are strong 24 μm and especially 70 μm emitters. With *SOFIA*/FORCAST and *SOFIA*/HAWC we will measure the spectral energy distributions (SEDs) of these dust enshrouded, emerging protostars over the wavelengths spanning their emission peaks. We will derive their bolometric luminosities and bolometric temperatures and thus sample the Class 0 and Class I protostar luminosity function down to fainter levels than possible with *IRAS* or with the recent *Spitzer* data alone. These observations will reveal whether these embedded objects have significant accretion luminosities, resolving the puzzle of whether the low luminosity Class I stars in Tau-Aur and elsewhere are ubiquitous or unique. Particularly important is the wavelength coverage and the far-infrared spatial resolution of *SOFIA* which removes the source confusion that has plagued previous *IRAS* and *Spitzer* investigations of similar phenomena.

Observing Summary:

Target	RA	Dec	F_{Jy}	Configuration/mode	Hours
TAU-AUR: 15 YSOS	04 15	+26	0.1 @21μm, 0.5 @100μm	2 FCAST, 4 HAWC	45
ρ OPH: 15 YSOS	16 28	−24.5	0.1 @21μm, 0.5 @100μm	2 FCAST, 4 HAWC	45
SERPENS: 15 YSOS	18 30	+01	0.1 @21μm, 0.5 @100μm	2 FCAST, 4 HAWC	45
NGC 1333: 15 YSOS	03 29	+31	0.1 @21μm, 0.5 @100μm	2 FCAST, 4 HAWC	45
				Grand total hours	180

Scientific Objectives

The collapse of a molecular cloud core leads to formation of a protostar that is initially deeply enshrouded by gas and dust. During the main accretion phase, the mass infall rate can be approximated by dividing the local Jeans mass by the free-fall timescale ($\dot{M}_{Infall} \sim M_J/\tau_{ff} = 5.4\,c_s^3/G$; Schmeja & Klessen 2004). For an isothermal sound speed, c_s, of 0.2 km/s characteristic of Taurus, this corresponds to $\dot{M}_{Infall} = 1 \times 10^{-5}$ M$_\odot$/yr. The effects of magnetic support can produce smaller infall rates (2×10^{-6} M$_\odot$/yr; Shu 1977) while the external compression in turbulent flows can produce larger infall rates (up to $\sim 10^{-4}$ M$_\odot$/yr, at least initially; Schmeja & Klessen 2004).

As first pointed out by Kenyon et al. (1990), however, if the infalling envelope material is channeled onto the star via steady-state disk accretion at the above rates, the liberated accretion luminosity would be roughly 10 times that emitted by the young photosphere. With such accretion dominated luminosities, young protostars should have total luminosities roughly 10 times those of neighboring T Tauri stars. This is seen for some objects but not for many others. Interestingly, the total bolometric luminosities (calculated by integrating the entire energy distribution of a star) of young objects in Tau-Aur show no statistically significant differences between objects exhibiting a wide range of infrared spectral indices. This discrepancy between the observed bolometric luminosities and the predicted accretion dominated luminosities is often referred to as the "Luminosity Problem" (Kenyon et al. 1990, 1994), and it implies that infrared spectral indices are not good indicators of circumstellar evolutionary states.

Specifically, the observed bolometric luminosity should have several contributors:

$$L_{tot} = L_{star} + L_{acc,shock} + L_{acc,disk} + L_{rep,disk}, \tag{1}$$

where L_{star} is the stellar luminosity, $L_{acc,shock}$ is the accretion luminosity generated as disk material impacts the star, $L_{acc,disk}$ is the viscously generated luminosity of the disk, and $L_{rep,disk}$ is reprocessed luminosity from the disk. The total luminosity can be simplified through substitution as

$$L_{tot} = 1.08 L_{star} + 1.58 L_{acc}. \tag{2}$$

Indeed, the total luminosities calculated by White & Hillenbrand (2004) based on measurements of $L_{acc,shock}$ and inference of $L_{acc,disk}$ and following the above prescription, agree very well with the bolometric luminosities for both Class I stars and Class II stars in Tau-Aur which were optically selected (median Class I $\log(L_{tot}/L_{bol}) = -0.16$, $\sigma = 0.57$; median Class II $\log(L_{tot}/L_{bol}) = 0.15$, $\sigma = 0.30$). For the Class I stars, this agreement suggests there is not a significant contribution to the bolometric luminosity generated from an infalling envelope supplying the disk with material at a high accretion rate.

For these Class I and Class II stars in Tau-Aur, the contribution of disk accretion ($L_{acc,shock} + L_{acc,disk}$) to the bolometric luminosity can range from a few percent to nearly 90 percent. However, in the typical case, only 28% of the bolometric luminosity is generated through disk accretion; the majority of the bolometric luminosity originates from the star. This result quantifies the "luminosity problem" for Class I stars in Tau-Aur, yet some Class

I stars there and many in the ρ Oph cloud *do* have significant accretion luminosities (Kenyon et al. 1990; Wilking et al. 1989; Greene & Lada 2002). Do these young stars in different clouds have truly differnt accretion properties, or do selection effects come into play? For example, the Tau-Aur clouds are nearby (140 pc) with low extinction ($A_v \sim 5$ mag), so optical and near-IR surveys there may be more sensitive to low luminosity young stars than similar surveys in the ρ Oph cloud (d $\sim$ 140 pc and $A_v > 25$ mag) or in more distant clouds in Ser or Per.

An additional remaining problem for Class I stars is the discrepancy between the accretion luminosity measured directly from shocked continuum and line emission at the stellar photosphere (as derived and discussed in White & Hillenbrand 2004), and the accretion luminosity required to reproduce the observed broad band spectral energy distributions from <1-1000μm (Kenyon et al. 1993a,b; Whitney et al. 1997, 2003a, ;Eisner et al. 2005).

One way to make progress in these areas is to obtain a more complete census of the Class I and the even more dust enshrouded Class 0 populations in several low mass star forming regions within several hundred parsecs. The bolometric luminosity distribution as a function of bolometric temperature (Myers & Ladd 1993) for known Class 0, Class 0/I, and Class I protostars is shown in Figure 1.

Recent *Spitzer* observations of molecular clouds within several hundred pc of the Sun are currently being conducted. (e.g. Figure 2). These surveys are revealing large numbers of sources which are visible only longwards of 8 μm, i.e. as 24 μm and 70 μm bright objects but with 8 μm flux densities <0.1 mJy. While initial sorting between contaminants (main belt asteroids and AGN, primarily) and true previously uncataloged young stars is ongoing, these surveys are expected to reveal hundreds of candidates for follow-up with *SOFIA*. Comparable, but limited, studies with ISO/ISOCAM revealed that the young protostar populations based on IRAS studies in clouds such as Chamaeleon I, Serpens, and L1641 were 40-400% incomplete (Persi et al. 2000; Kaas et al. 2004; Ali & Noriega-Crespo 2004). The increased sensitivity and more extensive mapping capabilities of *Spitzer* should increase the known Class I and Class 0 populations by more than an order of magnitude. Sensitive *Spitzer* observations will likely find any previously undetected low luminosity young stars embedded in star forming clouds, but they may be confused by *Spitzer's* low spatial resolution at far–IR wavelengths.

We therefore propose mid- and far-infrared imaging observations with *SOFIA* of such newly discovered objects with low bolometric temperatures. With *SOFIA*/FORCAST and *SOFIA*/HAWC we will measure the spectral energy distributions (SEDs) of these dust enshrouded, emerging protostars over the wavelengths spanning their peak emission. These observations are also likely to resolve many objects which are spatially confused in *Spitzer* images. We will derive their bolometric luminosities and bolometric temperatures and thus sample the Class 0 and Class I protostar luminosity function down to fainter levels than possible with *IRAS*, or with the recent *Spitzer* data alone in which sampling at only 1 or 2 wavelengths is possible. These observations will determine the accretion luminosities of these objects and resolve the extent of the luminosity problem once bolometric luminosities are correlated against bolometric temperatures.

Figure 1: Bolometric luminosity, determined by integrating a spectral energy distribution for a source at known distance, plotted against bolometric temperature, defined as the temperature of a blackbody with the same mean frequency as the source. The sample is all known Class 0 and Class 0/I sources within 500 pc (from Froebrich 2005). Known Class I objects would occupy 2/3 of the total area in the Figure, towards the lower right, and extend over the same luminosity range to bolometric temperatures as high as several hundred Kelvin. The currently known samples of Class 0 and Class I objects are biased against low luminosity sources; such objects are being identified in ongoing *Spitzer* surveys of galactic star-forming regions.

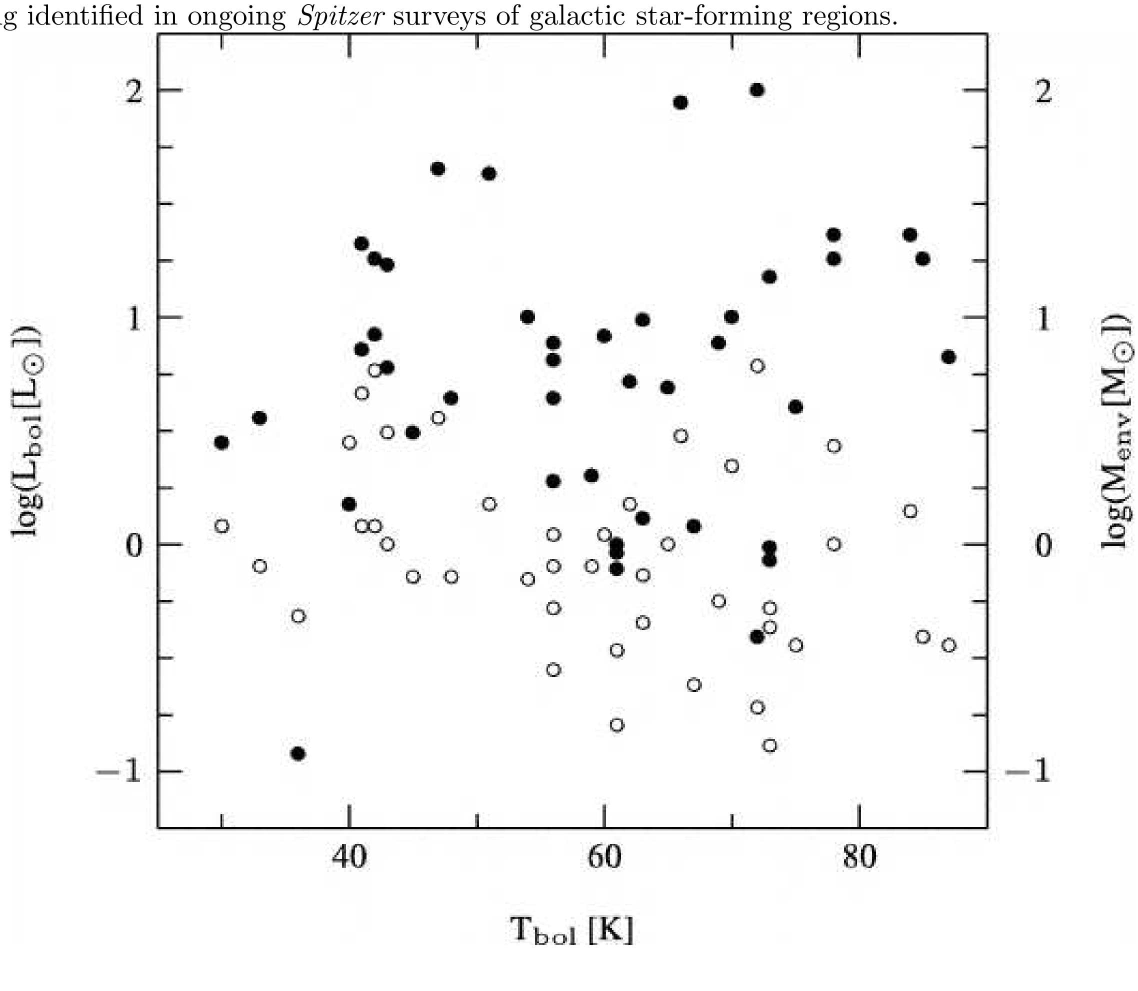
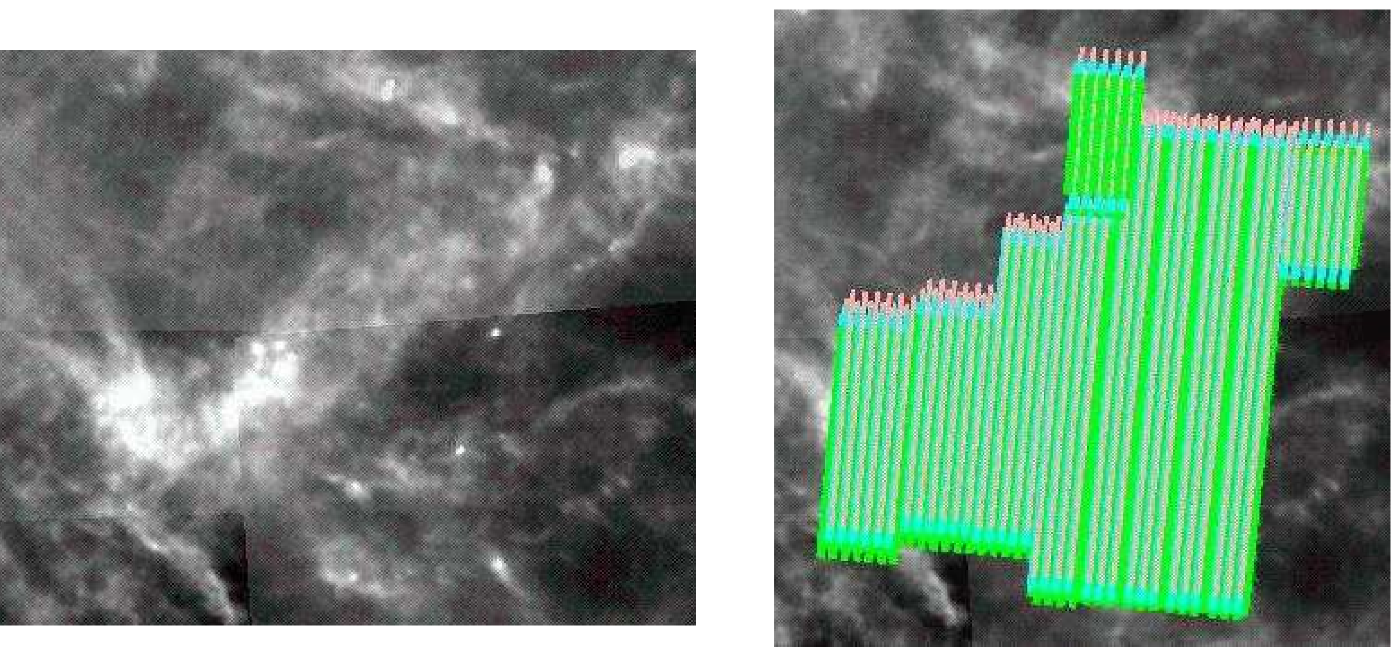


Figure 2: IRAS 60 μm map of the Taurus-Auriga star forming region with Spitzer AORs from the Padgett et al. IRAC and MIPS imaging survey overlayed on the right panel. This survey and others like it are expected to identify hundreds of previously unknown low luminosity Class 0 and Class I sources, increasing the population by more than an order of magnitude.



References

Ali, B. & Noriega-Crespo, A. 2004, ApJ, 613, 374

Eisner, J. A., Hillenbrand, L.A., Carpenter, J.M. & Wolf, S. 2005, ApJ, submitted

Greene, T. P., & Lada, C. J. 2002, AJ, 124, 2185

Kaas, A. A., et al. 2004, A&A, 421, 623

Kenyon, S. J., Hartmann, L. W., Strom, K. M. & Strom, S. E. 1990, AJ, 99, 869

Kenyon, S. J., Whitney, B. A., Gomez, M. Hartmann, L. 1993, ApJ, 414, 773

Kenyon, S. J., Calvet, N. & Hartmann, L. 1993, ApJ, 414, 676

Kenyon, S. J., et al. 1994, AJ, 107, 2153

Myers, P. C. & Ladd, E. F. 1993, ApJL, 413, L47

Persi, P. et al. 2000, A&A, 357, 219

Schmeja, S. & Klessen, R. S. 2004, A&A

Shu, F. H. 1977, ApJ, 214, 488

Whitney, B. A., Kenyon, S. J. & Gomez, M. 1997, ApJ, 485, 703

Whitney, B. A., Wood, K., Bjorkman, J. E. & Wolff, M. J. 2003, ApJ, 591, 1049

Whitney, B. A., Wood, K., Bjorkman, J. E. & Cohen, M. 2003, ApJ, 598, 1079

Wilking, B. A., Lada, C. J., & Young, E. T. 1989, ApJ, 340, 823

SOFIA Uniqueness/Relationship to Other Facilities

These observations are not feasible from the ground due to the wavelengths involved. The broad wavelength coverage and the far-infrared spatial resolution of *SOFIA* removes the source confusion that has plagued the few previous *IRAS* and *Spitzer* investigations of similar phenomena. The SOFIA/FORCAST spatial resolution at $\lambda = 24\mu$m is identical with *Spitzer*/IRAC at $\lambda = 8\mu$m. SOFIA/HAWC spatial resolution at $\lambda = 53\mu$m or 88 μm is very similar to *Spitzer*/MIPS at $\lambda = 24\mu$m; SOFIA/HAWC at $\lambda = 215\mu$m has spatial resolution identical to *Spitzer*/MIPS at $\lambda = 70\mu$m. This will allow direct use of both Spitzer and SOFIA data of different wavelengths to measure emission from the same spatial regions.

Observing Strategy

We predicate our observational strategy on the goal of detecting objects a factor of 100 less luminous than one of the brightest known Class I protostars in Taurus, IRAS 04016+2610 which has a bolometric luminosity of 3.7 $L_\odot$. This is also equivalent to detecting objects 100×, 30×, and 20× fainter than 04016+2610 in the ρ Oph, Ser, and Per (NGC 1333) clouds, respectively. To reach the required flux density limits at SNR=5-10 in the two longest FORCAST bands and all four HAWC bands for such a source with flux density 0.1 Jy at 21μm and 0.5 Jy at 100μm, requires roughly 1200 second integrations in each filter. Including overheads leads to a total time per source of 3 hours. Our program requires 180 hours of observatory resources for an initial set of 60 proposed targets distributed in the above 4 regions.

Special Requirements

The ρ Oph observations may require a southern deployment. These could be skipped in favor of more Tau-Aur, Ser, and Per targets if a deployment is not possible.

Maximum water:	medium
RMS pointing jitter:	2.0 as

Precursor/Supporting Observations

The proposed *SOFIA* observations are require the availability of new targets from various programs ongoing with the *Spitzer* mission. Many such observations are being conducted by the Cores to Disks Legacy program and by *Spitzer* General Observers.