June, 2008

Design Reference Mission Case Study
Stratospheric Observatory for Infrared Astronomy Science Steering Committee

Protostellar Cores in Infrared Dark Clouds

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Scientific category:	STAR FORMATION
Instruments:	HAWC
Hours of observation:	116

Abstract

We propose to use the SOFIA Stratospheric Observatory to obtain HAWC observations toward a sample of Infrared Dark Clouds (IRDCs), a new class of objects recently identified as mid-infrared extinction features in the Galactic plane. We have identified 10,961 IRDCs in the Galaxy, and using ^{13}CO and CS molecular line emission, have obtained reliable kinematic distances to more than 500 of those. Our molecular line and millimeter continuum data suggest that IRDCs are the cold molecular precursors to cluster forming clumps. They contain dense, cold cores with characteristic masses of ~ 120 M$_{\odot}$. These cores hold the key to understanding IRDCs and their role in massive star formation. Because IRDCs are cold, their thermal dust emission will peak in the far-IR regime, where the emission is optically thin. Thus, the far-IR is the best for probing the internal structure of IRDCs and identifing their star-forming cores. Our goal is to search for and characterize prestellar cores and to understand the initial conditions and earliest phases of high mass star formation by means of studying our sample of IRDCs cores. To achive this, we propose to obtain 53, 89, 155, and 215 μm HAWC images of 28 IRDCs containing multiple high-mass cores. These images will pinpoint the location of active star forming cores in IRDCs and, in conjunction with MIPS 24μm and JCMT/IRAM submm/mm images, allow the derivation of reliable masses, luminosities, temperatures, and dust emissivities. In order to derive these physical properties for a large range in core masses, the proposed observations will integrate a factor of about four deeper than the Herschel HiGal survey. This will allow us to probe the IRDCs down to lower column densities from which we can gain insights into their large scale structure. Moreover, these deep observations will provide complementary data to the HiGal survey and allow us to obtain a census of the IRDC cores in terms of evolution and multiplicity. The proposed observations will enable us to establish accurate 24μm to 53 μm to 1.2 mm SEDs towards a large sample of IRDC cores. The total requested observing time is 116 hours.

Table 1: The 28 proposed IRDC core maps with existing MIPS 24μm coverage

Source	$l(^o)$	$b(^o)$	major axis ($'$)	minor axis ($'$)	time (hours)
major axis ($'$)	minor axis ($'$)	time (hours)			
G028.67+00.13	28.6771	0.1319	14.6014	4.0792	6
G028.23-00.19	28.2353	-0.1912	12.1852	9.2477	12
G022.35+00.41	22.3568	0.4157	6.8819	5.4037	4
G019.27+00.07	19.2708	0.074	8.4024	1.8	2
G024.60+00.08	24.6057	0.0805	15.4156	7.4967	8
G025.04-00.20	25.041	-0.205	21.4960	6.4900	12
G028.08+00.07	28.0862	0.0714	2.1541	1.7205	2
G018.82-00.28	18.8219	-0.2847	14.1209	3.8833	4
G024.36-00.16	24.3623	-0.1619	2.6306	2.3324	2
G034.77-00.55	34.7712	-0.5572	6.6272	2.01	2
G030.97-00.14	30.9763	-0.1475	2.4413	2.2361	2
G028.53-00.25	28.530	-0.251	20.4167	5.0596	4
G036.67-00.11	36.6725	-0.1199	13.0736	5.8412	4
G023.60+00.00	23.6075	-0.0088	4.2426	0.8246	2
G028.10-00.45	28.1051	-0.4534	3.1241	2.01	2
G034.43+00.24	34.4374	0.2454	5.2953	2.01	2
G024.08+00.04	24.0835	0.0416	13.7753	12.3968	12
G024.33+00.11	24.3303	0.1135	6.1612	6	2
G030.57-00.23	30.577	-0.2361	5	4.1231	2
G030.14-00.06	30.1481	-0.063	7.912	5.2154	2
G035.39-00.33	35.3951	-0.3359	20.6155	6.4405	6
G027.97-00.42	27.9744	-0.4213	2.8425	2.01	2
G015.31-00.16	15.315	-0.169	22.2800	7.3348	8
G024.42-00.23	24.4295	-0.2357	1.9698	1.8439	2
G033.69-00.01	33.6957	-0.0185	10.7648	6.5054	4
G027.75+00.16	27.7526	0.163	5.4918	3.5777	2
G053.31+00.00	53.3153	0.003	1.6125	1.6125	2
G018.58-00.08	18.5886	-0.0847	6.6483	2.0396	2
total time					116

Scientific Objectives

Infrared (IR) surveys of the Galactic plane, performed with the Infrared Space Observatory (ISO) and Midcourse Space Experiment (MSX) satellites, have identified an entirely new class of objects, the Infrared Dark Clouds (IRDCs). These clouds are seen in silhouette against the bright Galactic background at mid-IR wavelengths (Perault et al. 1996; Carey et al. 1998; Hennebelle et al. 2001). Preliminary studies show that they have high densities ($> 10^5$ cm^{-3}), high column densities ($\sim 10^{23} - 10^{25}$ cm^{-2}), and low temperatures (< 25 K; Egan et al. 1998; Carey et al. 1998, 2000). Until recently, it was unclear what role IRDCs play in star formation. Although Egan et al. (1998) suggested that IRDCs are quiescent, isolated molecular clumps, unrelated to star-formation, the detection of compact mm (Rathborne et al. 2006) and sub-mm (Lis & Carlstrom 1994; Carey et al. 2000) continuum sources toward some IRDCs suggests that they harbor pre-stellar cores. These pre-stellar cores hold the key to understanding IRDCs and their role in star formation.

In order to study and characterize IRDCs, we have embarked on a systematic multi-wavelength study. First, we have identified and cataloged 10,961 IRDCs (Simon et al. 2006a) in the MSX 8 μm Galactic Plane survey by selecting regions of high contrast relative to the bright extended mid-IR Galactic background. Next, we established the first large IRDC sample with known distances. We have found more than 500 IRDCs with clean morphological matches in distinct velocity channels of ^{13}CO (1-0) molecular line emission (from the Boston University - Five College Radio Astronomy Observatory Galactic Ring Survey) or distinct CS (2-1) velocity components (observed with the Mopra telescope; Jackson et al. 2008). Fig. 1 shows examples of ^{13}CO (1-0) spectral line observations. With these velocities we can determine kinematic distances to the IRDCs. Because IRDCs are seen as extinction features in the Galactic plane, they unambiguously lie at the near kinematic distance. This method is the only known technique for estimating distances to IRDCs. With the kinematic distances, we have now obtained, for the first time, good estimates of the sizes, masses, and Galactic distribution for a large sample of IRDCs.

Remarkably, the Galactic distribution of IRDCs (in the first quadrant) peaks at a Galactocentric radius of ~ 5 kpc, precisely coinciding with the so-called 5 kpc molecular ring, the Galaxy's most massive and active star forming structure. The fourth quadrant IRDCs show a pronounced peak in their radial Galactocentric distribution at 6 kpc. This disparity suggests that IRDCs here trace a spiral arm which lies closer to the Sun in the fourth quadrant. The IRDC distribution matches very well the location of the Scutum-Centaurus arm in Milky Way models dominated by two spiral arms.

This correspondence of IRDC locations and large scale Galactic star forming structures suggests a close connection between IRDCs and star formation. Of the 350 IRDCs with known kinematic distances in the first quadrant, we have selected the 56 darkest IRDCs (those with $> 35\%$ contrast at 8μm with respect to the mid-IR background in MSX) for detailed study. This sample, the IRDC Known Distance Sample (IRDC KDS), spans a large range in distance and Galactic environment. Most of the clouds in the IRDC KDS have been imaged in the mm continuum and all have been imaged at $3.5 - 8\mu$m with the GLIMPSE and at 24 μm with the MIPSGAL Spitzer Legacy projects. The characterization of these IRDCs and their protostellar cores in the far-infrared is the goal of this proposal.

Given the kinematic distances, we have used molecular line and mm continuum data to estimate characteristic sizes of ~ 5 pc and masses of a few 10^3 $M_\odot$ (Simon et al. 2006b) for the IRDCs. These sizes and masses are too large for the formation of individual low-mass stars. However, the cores here often seen as mm/submm peaks within IRDCs are similar in size as what is typical for molecular *hot cores* (0.1-0.5pc size) that have recently formed massive stars. *We conclude that IRDCs are the cold, dense precursors to cluster forming clumps. They are the densest clumps in newly formed molecular clouds, which are just beginning the process of fragmentation and condensation. IRDCs, therefore, are important new laboratories to study the pristine, undisturbed physical conditions of cluster forming clouds before they are shredded apart by winds and radiation.* Further support for this idea comes from the detection at mm (Rathborne et al. 2006, Beuther & Sridharan, 2007), and sub-mm (Lis & Carlstrom 1994; Carey et al. 2000) wavelengths of compact, cold dust cores within IRDCs. We have recently observed the IRDC KDS with the IRAM telescopes at 1.2 mm (Rathborne et al. 2006). The morphology of the mm emission matches the 8 μm extinction extremely well (Fig. 1). All IRDCs show compact, cold dust cores superimposed on extended emission. These unresolved cores have characteristic masses of ~ 120 $M_\odot$ and are almost certainly massive proto-stellar cores.

Preliminary Spitzer data toward IRDC mm cores have been key to understanding their true nature. GLIMPSE IRAC images have shown that some of the IRDC mm cores are associated with fuzzy, faint 4.5 μm emission, which may indicate that the cores are the sites of active, embedded star formation. When we compare these *active* regions to *quiescent* regions with no 4.5 μm emission, we find that the active regions have enhanced linewidths in SiO molecular lines, a well known indicator of massive star formation (see Fig. 2). Other high density tracing molecular lines, such as HCN (4–3) and CS (3–2), also show these enhanced linewidths and indicate extremely high densities. Although suggestive, these findings remain inconclusive because of the large 8 μm extinction toward IRDC cores and the possibility of confusion with extincted background sources. Fortunately, MIPS data at 24 μm provide the key diagnostic test that unambiguously demonstrates embedded star formation within IRDC cores. In 24 μm MIPS images both from our own images and the MIPSGAL survey (Fig. 3), most IRDCs remain dark at 24 μm, indicating extremely high column densities and low temperatures. Moreover, their 24 μm extinction morphologies exactly match the morphologies of the 1.2 mm continuum emission and the 8 μm extinction in the GLIMPSE images. Surprisingly, however, 37 of 140 mm cores (about 1/4 of the total) were found to contain bright 24 μm emission sources (see Fig. 3). The addition of the 24 μm data point to the mm and submm spectral energy distributions (SEDs) toward these cores conclusively demonstrates that some show very large bolometric luminosities ($\sim 2,000$ to 40,000 $L_\odot$). In contrast, the quiescent, cold cores are much less luminous, $\simeq 100 L_\odot$, (Fig. 4). For example, in IRDC 43, the SEDs reveal the importance of the 24 μm data point (Rathborne et al. 2005). IRDC 43 contains three cores with quite similar 1.2 mm fluxes. The 24 μm fluxes, however, vary by at least 3 orders of magnitude. Strong far infrared emission then is the key indicator of large bolometric luminosities and warm dust. Because the luminosities toward the bright 24 μm cores must arise from internal (proto)stellar sources, strong 24 μm emission can unambiguously demonstrate the presence of protostars within IRDC cores. Thus, MIPS 24 μm data conclusively reveal that some IRDC cores are the sites of active star formation. Before Spitzer, it was unclear if any IRDC was a site of active star formation. Now it is obvious that in at least some cases we are seeing the earliest evolutionary stages in the birth of massive stars.

The characteristic sizes (<0.5 pc) and masses ($\sim$120 $M_\odot$) of IRDC cores are quite similar to those of the 'hot cores' associated with an early stage of high-mass protostellar evolution. Consequently, the cold IRDC cores may represent an earlier evolutionary phase of high-mass protostars that will eventually evolve into 'hot cores.' If so, then we should be able to find IRDCs in which this transition has already taken place. Although our investigation has just begun, we have already found at least two examples of 'hot cores' in IRDCs. Our Submillimeter Array (SMA; Rathborne et al. 2008) and mm Plateau de Bure Interferometer (PdBI; Rathborne et al. 2007) interferometric observations clearly reveal the unmistakably rich molecular spectrum of 'hot cores' embedded in two IRDC cores, while spectra toward a quiescent core are consistent with cold, dense gas.

High-mass stars do not form in isolation; rather, they form as part of star clusters. For example, the best studied high-mass star forming region, Orion, contains 4 young O stars in the Trapezium surrounded by $\sim$3500 lower-mass stars (Hillenbrand 1997). If IRDCs are 'proto-Orions', as the evidence suggests, then the high-mass protostars in IRDC cores should be accompanied by a large number of lower-mass protostars as the IRDCs form a protocluster.

Observational evidence for lower-mass protostars, however, is difficult to obtain. Because the high-mass protostars are much more luminous than lower-mass protostars, they are far easier to detect. Moreover, since the lower-mass protostars should be found in close proximity (within, say, 0.5 pc), one requires excellent angular resolution to separate them from their high-mass counterparts. To detect the lower mass protostars, then, requires excellent sensitivity, angular resolution, and dynamic range. We have begun this search with mm/submm interferometery and with large ground-based infrared telescopes, and initial results are promising. At high angular resolution, many IRDC cores break up into multiple condensations, with one massive object accompanied by several lower mass objects (Rathborne et al. 2007). Although we have only imaged a few protoclusters, early results are consistent with a Salpeter initial mass function. Furthermore, a comparison of IRDC core properties, such as size mass, mass density, and stellar number density (Rathborne et al. 2007), with those of cluster-forming molecular clumps such as the Trapezium, IC 348, and NGC 2024 (Lada et al., 2003) shows remarkable similarities. All of the initial evidence suggests that IRDCs are forming protoclusters.

We aim to build on these findings of the IRDC mm cores. We wish to answer the following questions: Is massive star formation common in IRDC cores? What is the evolutionary sequence, and the relative timescales spent in various stages, of the IRDC mm cores? What are the differences between the quiescent and active cores? To answer these questions, we propose SOFIA observations with HAWC to measure the far-IR SEDs toward our sample of 1.2 mm continuum cores with 24 μm MIPS observations. Because the cores have SEDs that peak in the far-IR, it has been very difficult to estimate reliable bolometric luminosities. So far, we have been forced to interpolate from a few mm/submm data points. By measuring the 53 to 215 μm SEDs directly, and comparing these with our 24 μm MIPS and mm/submm fluxes, we can accurately deduce the bolometric luminosities, the dust temperatures, and the dust emissivity index. This information is critical to investigate the physical differences between the active and quiescent cores. The range of bolometric luminosities will provide information on the embedded YSOs, their evolutionary states, and their masses. The angular resolution will be 4 - 40". By comparing the data to models of embedded stars, the dust temperatures will also help distinguish between single massive stars or small groups of lower mass stars. Since active star formation may destroy small dust grains, we expect that the emissivity index may vary between the two types of cores. In order to obtain sufficiently precise spectral indices, high sensitivity observations will be required. Therefore, we need long integrations (between 2 and 12 hours per filed) for our selected set of observations proposed here. These observations will provide a very valuable complimentary set of IRDC observations to the shallower data expected from the Herschel HiGal 70 to 500 μm survey over the whole Galactic plane ($|b| < 1$ deg) at sensitivities 80-120 mJy (4 sigma).

References

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■ SOFIA Uniqueness/Relationship to Other Facilities

Ground based facilities are hindered by poor sensitivity, small fields of view, and little to no atmospheric transmission in the far-IR. In the near future SOFIA and Herschel will be the only facilities able to conduct these observations in the far-IR up to 215 μm wavelength,

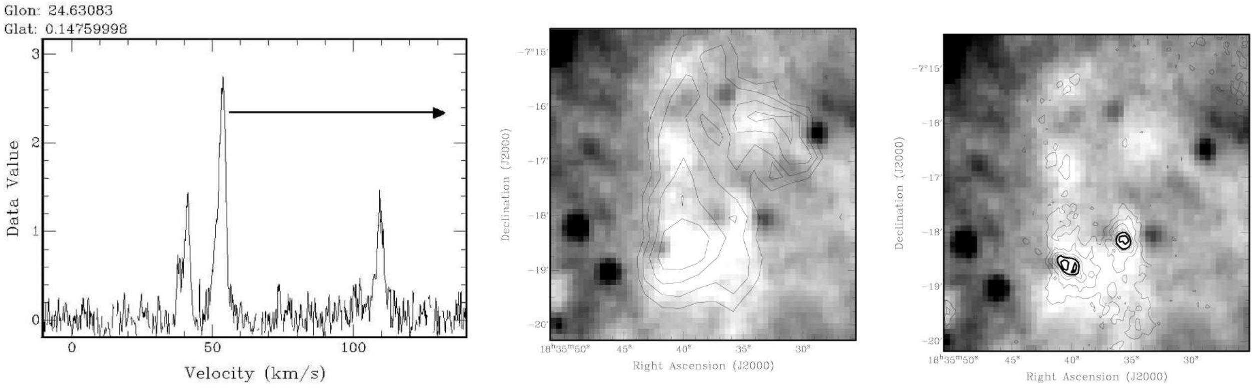

Figure 1: Left: The ^{13}CO spectrum along the line of sight toward this IRDC, showing three distinct clouds. Morphological similarities between the IRDC and the integrated ^{13}CO emission for the component at 52.3 km s^{-1} allow us to unambiguously establish a distance to the IRDC (3.6 kpc). Middle: MSX 8 μm image in reverse grey-scale with contours of ^{13}CO emission (integrated over 49 - 55km s^{-1}, $v_{\rm lsr}$ peak of 52.3k ms^{-1}) showing the morphological similarities. Right: MSX 8 μm image in reverse grey-scale with contours of 1.2 mm continuum emission. Note that the 1.2 mm continuum emission reveals compact, massive protostellar cores.

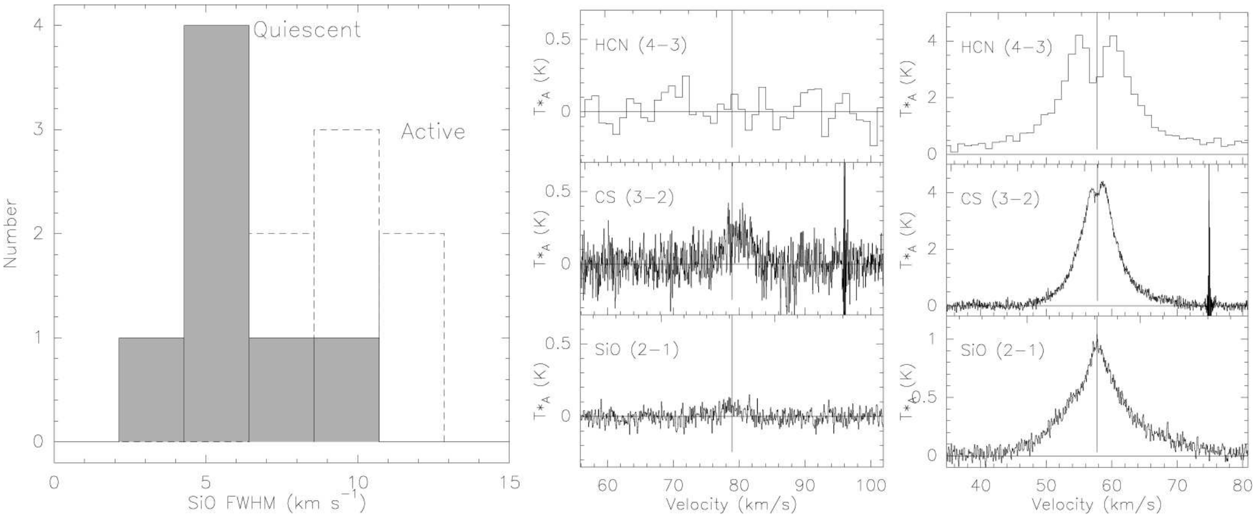

Figure 2: Histogram of the width of the SiO(2-1) line for quiescent and active cores (left). HCN (4-3), CS(3-2), and SiO(2-1) spectra for a quiescent (middle) and active (right) core. The solid line marks the velocity of the core.

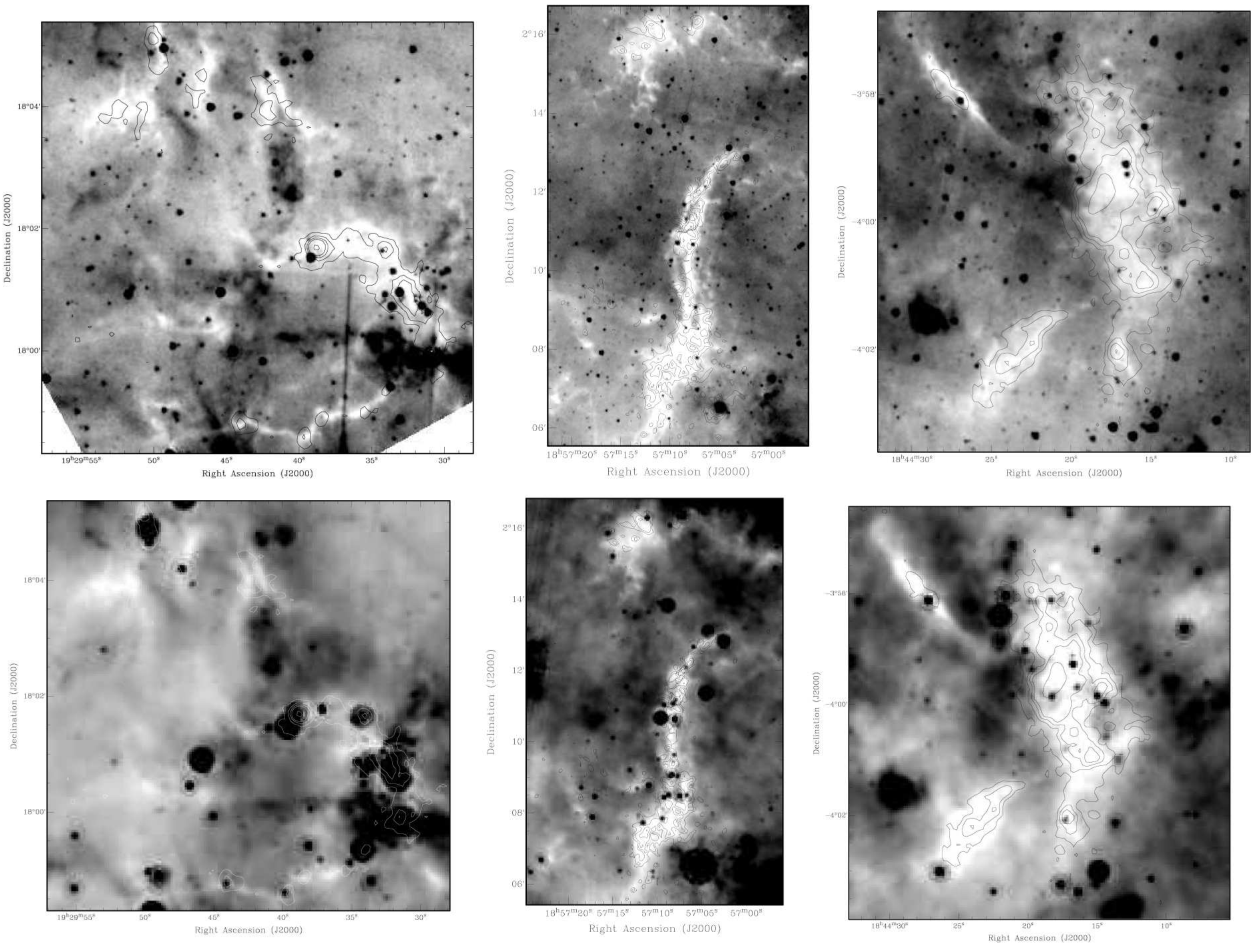

Figure 3: Spitzer images (8 μm top and 24 μm bottom) in reverse grey-scale with contours of 1.2 mm emission. Note the striking morphological similarities between the mid-IR features and the extended 1.2 mm continuum emission, and the many compact sources within the IRDCs. The active star forming cores are revealed by bright 24 μm emission (lower left panel) while quiescent cores remain dark (lower middle and lower right panels).

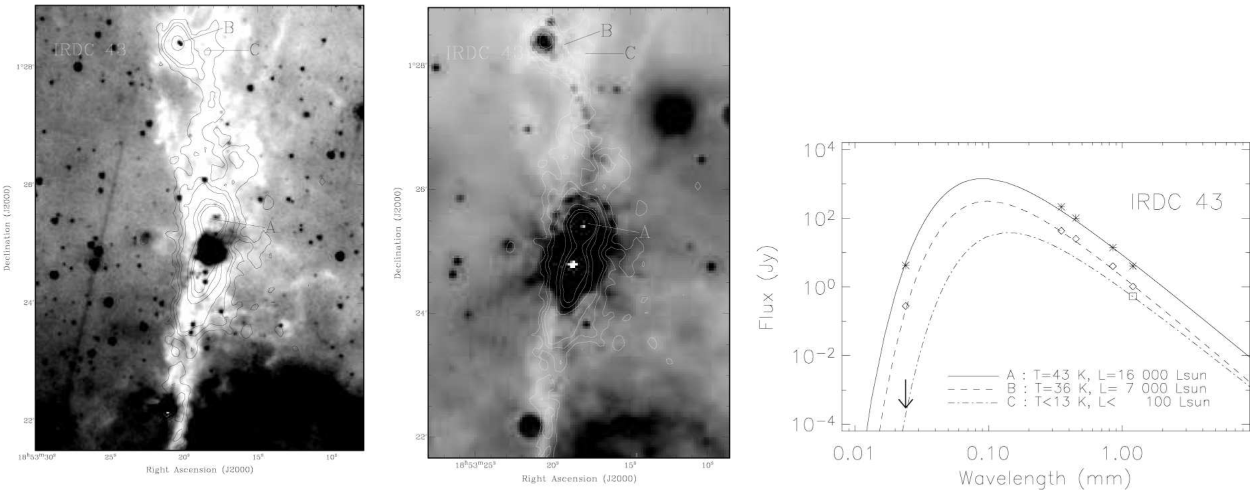

Figure 4: Left: GLIMPSE 8 μm image in reverse gray-scale with contours of 1.2 mm con- tinuum emission (levels are 60, 90, 120, 240, 360, 480 mJy beam^{-1}). Middle: MIPS 24 μm image in reverse gray-scale with 1.2 mm continuum contours. Right: SEDs for three IRDC mm cores (A, B, and C). The parameters derived from the curves are labelled.

and, where the coverage overlaps with Spitzer, SOFIA provides significantly higher angular resolution (but is slightly less than that of Herschel). At the ~ several kpc distance of these objects, SOFIA will be critical for obtaining sufficient spatial resolution to resolve the individual cores, in particular at the long wavelengths. HAWC's angular resolution of order 10 arcsec will not only well match Spitzer's at 24μm, but also the angular resolution of ground based (sub)millimeter observations with the CSO, JCMT, IRAM 30m and other telescopes. HAWC's large number of pixels, combined with the fact that IRDCs are strong FIR emitters (Fig. 4, right panel), makes it an ideal instrument for very efficiently obtaining maps of these object.

Many of the IRDCs will be prime targets for future space (Herschel) and ground based high angular resolution observations with interferometers such as ALMA and CARMA. There are three Herschel key programs with clear science overlap with this proposal. Two of those (HOBYS and KPGT), however, target specific sources which, as far as we can tell, will have no overlap with our sample. HiGal (a 70 to 500 micron survey over the whole Galactic plane $|b| < 1$ deg) will provide a very large data base for IRDCs, but only with sensitivities of ~ 80-120 mJy (4 sigma). Future interferometric observations of IRDCs will address some of the open key questions in massive star formation, e.g., what is the degree of fragmentation (clustering) and the mass distribution on the smallest scales and their connection to the IMF. The SOFIA observations are invaluable preperatory work for such future studies.

Observing Strategy

We intend to observe our 28 IRDCs in the four HAWC bands. We will obtain maps with typical sizes between 10 and 150 arcmin^2 (see source list for details) of our sample of 28 MIPS 24 μm maps around the millimeter cores. By measuring the 53 to 215 μm SEDs directly, and comparing these with our 24 μm MIPS and mm/sub-mm fluxes, we can accurately deduce the bolometric luminosities, the dust temperatures, and the dust emissivity index .

Observing time estimate: The following is a list of HAWC 4σ sensitivities per beam achieved in 900 s integration time: 53 μm: 62 mJy; 89 μm: 40 mJy; 155 μm: 40 mJy; 216 μm: 32 mJy. Based on the SEDs (Fig. 4, right), we expect the faintest and most quiescent IRDC cores to have fluxes of or less than 100 mJy at 53μm and $\sim$ 10 Jy at the longer wavelengths ($89 - 215\mu$m). The brightest and most active cores within the IRDCs will probably be a few 1000 Jy at these wavelengths. Furthermore, at 53μm, the FOV of the HAWC array will be smallest. To detect the most quiescent cores at 53μm with sufficient signal to noise, we need to use an integration time of 2400s. This integration time will give us a MDCF (minimum detectable continuum flux; for a S/N = 4 per beam) of 40 mJy at 53μm. The other bands require significantly less integration times. Considering overheads we conclude that for single pointings (or small maps) for all four bands an average of 1 hour observing time will be sufficient per source. For the maps we assume a minimum of 2 hours with longer observing times for the very extended sources, see Table 1 for individual time estimates. In total we request 116 hours of observing time.

Special Requirements

Put any special requirements in text here (e.g. like requires FORCAST grism), or just uncomment and fill in parameters below.

Maximum water:	medium
RMS pointing jitter:	2.0 as

Precursor/Supporting Observations

We have obtained observations ranging from millimeter to the mid-infrared for the proposed targets. See section “Scientific Objectives” above for a detailed description of those observations.