Deep Surveys for Far-IR Luminous Galaxies

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Scientific category:	DISTANT GALAXIES
Instruments:	HAWC
Hours of observation:	123

Abstract

Dust extinction in galaxies is a very important phenomenon. It reveals the interstellar medium, but complicates our view of galaxy formation, especially the formation of the most luminous and massive galaxies. To overcome and quantify the effects, it remains essential to image forming galaxies at far-IR wavelengths that are inaccessible from the ground. The 2.5-m aperture of SOFIA provides an advantage over existing space platforms, in that the confusion noise that limits the depth to which surveys can find these galaxies is mitigated by the better angular resolution it provides. As a result, SOFIA can image fainter than *Spitzer*, and HAWC's high-quality 2-D imaging array allows a faithful image of the sky to be constructed. Using HAWC at 215 μm we propose to target well-studied fields containing a sample of known high-luminosity, high-redshift galaxies, to better locate the peak of their spectral energy distributions (SEDs), and thus reveal accurate luminosities, and to discover serendipitously new far-IR-luminous galaxies that are too faint for existing images to have found. This program must be carried out before the PACS and SPIRE instruments on *Herschel* are available.

Observing Summary:

Target	RA	Dec	F_{Jy}	Configuration/mode	Hours
SUBARU-XMM	02 18	-05 00	0.05	HAWC-215	24
A370	02 39	-01 35	0.05	HAWC-215	6
COSMOS	10 00	00 00	0.05	HAWC-215	24
GOODS-N	12 36	+47 00	0.05	HAWC-155/215	39
EGS	14 30	+52 30	0.05	HAWC-215	24
A2218	16 35	+66 13	0.05	HAWC-215	6
				Grand total hours	123

Scientific Objectives

The effects of dust obscuration for reprocessing the radiation from star formation and AGN activity in galaxies into the far-IR waveband has been known to be very important at both high and low redshift since the *IRAS* mission in the 1980's. *IRAS* yielded a large sample of dust-enshrouded galaxies to study (Soifer et al. 1986), and *COBE* since found comparable cosmic background radiation intensities from the galaxy formation process at far-IR and optical wavelengths (as first detected by Puget et al. 1996, and compared with the optical/near-IR background in Fig. 1). The *ISO* and *Spitzer* missions added much more sensitive probes of deep fields and known galaxies; *Spitzer* now provides excellent images of the sky at wavelengths of $24\,\mu$m and shorter. However, its imaging performance at the wavelengths of 70 and $160\,\mu$m is limited by the modest resolving power of *Spitzer*'s 0.85-m primary mirror. It is at these, and longer, wavelengths that the peak of a galaxy's spectral energy distribution is found.

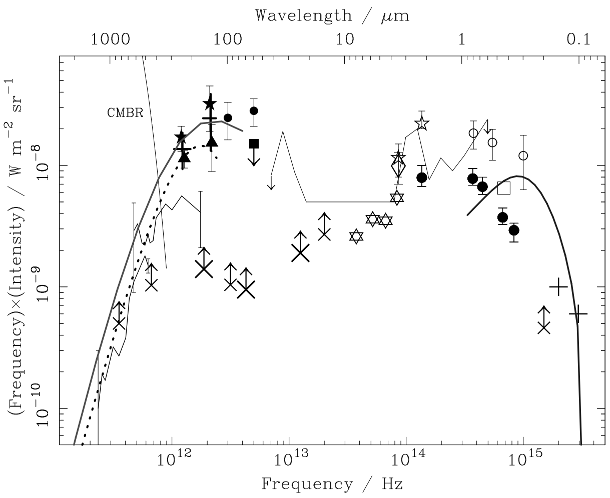
The power of dust-enshrouded galaxies evolves strongly with increasing redshift, increasing by a factor of 10-20 out to $z \simeq 1$ (See a compilation of the current data in Fig. 2), and so the study of galaxies at far-IR wavelengths remains important in the deepest possible observations.

Based on two decades of follow-up observations, the presence of merging and interacting galaxies containing AGN in the most luminous *IRAS* galaxies is well established, while the fainter and more distant samples of galaxies from *ISO* and *Spitzer* surveys typically follow a similar pattern. Far-IR luminous galaxies thus include the most active and extreme examples of the population of galaxies.

At longer submm wavelengths, high-mountain observatories have detected a population of high-redshift 'submillimeter galaxies' (SMGs; Blain et al. 2002) that have properties similar to the most luminous galaxies detected by *IRAS* at $z < 0.1$. These SMGs are much more luminous than the typical optically-selected high-redshift galaxy. Despite this large luminosity, they are sufficiently common to contribute a significant fraction ($\simeq 20\,\%$) of the total luminosity of all high-redshift galaxies (see Fig. 2). Hence SMGs, and their fainter cousins, must be accounted for in a full census of the history of galaxy formation activity. Furthermore, because far-IR luminous galaxies cannot be identified easily using optical colors, direct far-IR observations are *necessary* to support faint near-IR/optical surveys from *HST*, *JWST* and large ground-based telescopes. Distant SMGs are more enigmatic than the *IRAS* galaxies, but typically also show extended optical structure, are seen to contain AGN from X-ray and optical spectroscopy, and have dynamical signatures in CO observations consistent with major mergers.

It is plausible that the SMGs represent the forming large bulges of spirals and elliptical galaxies. They could thus reveal the formation of most of the stars in galaxies in the local Universe. SMGs also appear to be found preferentially in the densest regions of the evolving web of cosmic structure, and so could signpost the most extreme active regions of the high-redshift Universe that are difficult to locate in other ways (via radio, X-ray or optical photometry), without the cost of the extensive optical spectroscopy that is required

Figure 1: A compilation of measurements of the background radiation intensity from galaxies (updated from Blain et al. 2002), showing two comparably-intense peaks, at near-IR and far-IR wavelengths. The enhanced resolving power of SOFIA-HAWC will allow between 2 and 3 times more of the far-IR peak of the background radiation spectrum to be resolved into galaxies in the 215/155 μm windows than achieved by *Spitzer* (larger diagonal crosses), providing more insight into the redshifts, luminosities and evolution of the galaxies that supply the peak of the far-IR component of the background.



to sift through the sample to reveal large-scale structures in the radial direction out into the Universe.

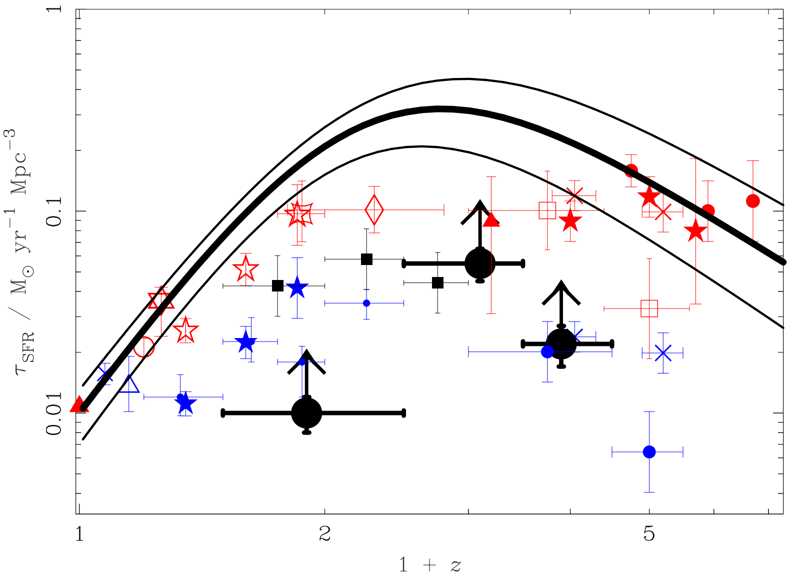
The role of deep observations with SOFIA is both to better quantify the properties of known SMGs, to accurately determine their SEDs and true luminosities, and to find fainter examples of the galaxies identified by *Spitzer*, to account for a significantly larger fraction of the galaxies responsible for the far-IR background radiation.

The redshifted peak of the far-IR SED of known SMGs, lying at 200-300 μm for z = 2-3, can be traced using images from HAWC in concert with existing ground-based submm observations, leading to accurate luminosities, as the far-IR emission of these galaxies dominates that at other wavelengths.

Few high-redshift far-IR galaxies are known with properties intermediate between the well-studied and very numerous samples of optically-selected Lyman break galaxies (LBGs) identified using 4- and 8-m telescopes (Steidel et al. 2004) and the SMGs, which are 10 times more luminous in the far-IR than the LBGs: such a population of 'bridging' galaxies would lie in the 10-100 mJy flux density range, which is deeper than the confusion limit of *ISO* and *Spitzer*. HAWC can detect such bridging galaxies at the peak wavelengths of their SEDs in the fields surrounding SMGs targetted for SED determination above. *Spitzer* can detect these galaxies readily at 24 μm, but the addition of SOFIA-HAWC observations is important: as for the SMGs HAWC data will provide much more accurate SEDs and luminosities.

The advantage of a deep HAWC survey over existing work is threefold:

Figure 2: The rate of formation of stars in galaxies inferred from an array of multiwavelength observations. The small colored points show results from optical and near-IR surveys. The solid lines show the inferred properties of the whole dust-enshrouded far-IR-luminous population (Blain et al. 2002). The large filled circle lower limits show the inferred contribution from SMGs with secure redshifts (Chapman et al. 2005). At $z \simeq$ 1-2 SOFIA-HAWC will detect a larger fraction of the total population, better revealing the nature of the galaxies making up the difference between these lower limits and the fitted curves.



1. A larger proportion of the background radiation will be associated with detected galaxies, thus providing better constraints on the evolution of otherwise hard-to-study far-IR-luminous galaxies.

2. The SEDs and luminosities of known very luminous far-IR galaxies will be established very securely.

3. A fraction of the unprobed galaxies that bridge the far-IR luminosities of well-studied LBGs and SMGs will be identified and become available for detailed study.

References

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Chapman S.C. et al., 2005, ApJ, 622, 772
Kneib J.P. et al., 2005, MNRAS, in press (astro-ph/0409502)
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Steidel C.C. et al., 2004, ApJ, 604, 534

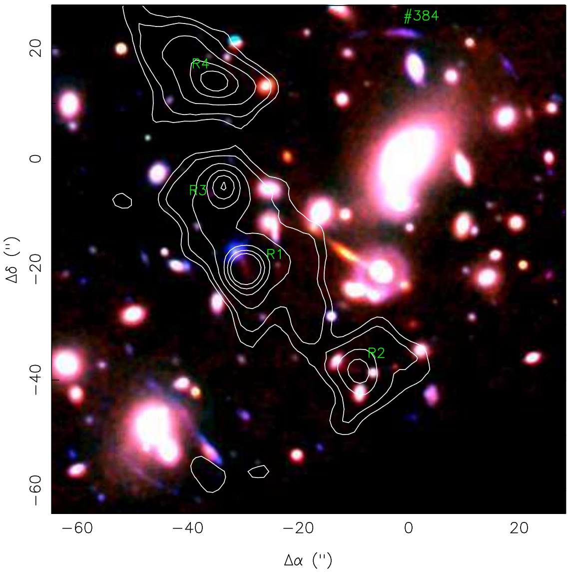
SOFIA Uniqueness/Relationship to Other Facilities

Prior to the launch of *Herschel*, SOFIA will be the largest aperture far-IR-sensitive telescope available, and the only telescope with a deep confusion limit at 100-200 μm. The key difference between *Spitzer* and SOFIA is that the SOFIA-HAWC confusion level is expected to be 3.3 times less at 215 μm (and 8 times less at 155 μm) as compared with the *Spitzer* confusion level at 160 μm. *Herschel*'s confusion limit is improved by an additional factor of about 50%. SOFIA observations thus offer to push our knowledge of the properties of faint far-IR galaxies further than *Spitzer*, by detecting a modest number of high-redshift examples fainter than the *Spitzer* observations can identify. SOFIA-HAWC can thus accurately define the nature of the population of galaxies that *Herschel* will be able to detect in greater numbers. Once *Herschel* is observing, its PACS and SPIRE instruments will be much more efficient than SOFIA-HAWC for carrying out these observations, because they have no atmospheric noise burden and a larger primary mirror.

The high-resolution spatial details of galaxies detected using HAWC with a 215-μm resolution of 22 arcsec (see Fig. 3) can be revealed using ALMA in a snapshot lasting a matter of minutes, and the brightest can be imaged in much longer integrations with the SMA/CARMA interferometers. However, these ground-based instruments do not provide the spectral range to measure accurately either the shape or absolute peak value of their SEDs. A large ground-based single-aperture submm telescope like CSO/JCMT/APEX can provide better spatial resolution than SOFIA-HAWC at 350/850 μm; however, despite this, these telescopes are not able to resolve the internal structure of the galaxies they target. SOFIA's ability to quantify the shape of the SED peak and thus the total luminosity very accurately for far-IR luminous galaxies is a great advantage.

The advantage of SOFIA over existing facilities extends to the 89-μm HAWC filter; however, we do not propose to observe at this wavelength at this stage, at which the advantage as compared with the 70-μm channel of *Spitzer* is not so dramatic. For accurate follow-up observations of detected galaxies, this could be a very valuable band, however, with no effective confusion limit (a 660 hr integration would be required to reach the confusion limit), and a useful detection likely for an SMG in of order 50 hr of integration.

Figure 3: An 850-μm image of submm-selected galaxies in the cluster Abell 2218 (contours: Kneib et al. 2005), overlaid on a multicolor optical image. This emphasizes the large difference between the optically and far-IR selected galaxy population, which HAWC will help to bridge. HAWC can image with a resolution of 22 arcsec at 215 μm: a little coarser than the 15-arcsec resolution of the submm image. The central 3 submm galaxies (R1, R2 and R3) are gravitationally lensed images of the same background galaxy with a total magnification by a factor of about 40. The short axis of the HAWC field of view at 215 μm is a little less than the size of the image, and the long axis is about 2.5× greater in extent.



Observing Strategy

In the HAWC bands (53, 89, 155 and 215 μm), confusion noise ensures that the secure detection of a galaxy can probably only be made down to a flux of order 0.045, 1.1, 14 and 34 mJy respectively (Blain et al. 2002). At the longest two wavelengths, the HAWC sensitivities ensure that the confusion limits can be matched in about 28 and 2.0 hr respectively at the 3-σ level (for point source, 1-σ 1-hr sensitivities of 25 and 16 mJy respectively). As a result, SOFIA at 215 μm can be used to make practical images much deeper than *Spitzer* in small fields. We propose to observe target SMGs primarily in the 215-μm filter: this yields the largest field of view (96×256 arcsec; see Fig. 3), best match the redshifted peak of the SED of the target galaxies, and to provide a long wavelength baseline as compared with ground-based submm observations and measurements in the very sensitive *Spitzer*-MIPS 24-μm channel.

Confusion is due to the effects of fainter, overlapping sources: more precise determinations of confusion of course await commissioning observations. Where the position of a galaxy is known accurately a deeper observation can be possible, but at the expense of reliable identification of nearby sources that are found serendipitously in the field. To observe as deep as necessary will require an extended staring observation for several to 10's of hours per field, with telescope nodding, chopping or dithering to ensure accurate sky background subtraction. The optimal mode for deep integrations will be determined after commissioning, and we will exploit the best practice to obtain the best sensitivity. The proposed observations are the longest that will probably be carried out using HAWC, being matched to the confusion or dynamic noise level subject to verification during commissioning.

Alongside imaging a specific target SMG in each 215-μm HAWC field , we will detect far-IR luminous galaxies previously unidentified, that can be studied by comparison with archived deep radio, optical and *Spitzer* 24-μm MIPS and $3 - 8\,\mu$m IRAC data in the field. Subject to revised confusion and sensitivity estimates, we propose to integrate for 6 hr at 215 μm, reaching a 5σ flux limit of 33 mJy,

We also propose a single parallel 155-μm band images in the center of our best-surveyed target field, GOODS-N, covering the 72×192 arcsec 155-μm field of HAWC. We will thus be able to evaluate the utility of two-band techniques for reducing confusion, using the better resolution at the shorter wavelength to identify correlated spatial structure due to the common population of far-IR emitters that contribute to both bands. This is likely to be a technique that will be exploited by the PACS/SPIRE instruments on *Herschel*: SOFIA can prototype this approach. We propose to observe for 15 hr at 155 μm, reaching an identical 5σ flux limit of 31 mJy. If multi-band confusion mitigation is successful, then we could usefully increase the integration time at 215 μm to increase the number of detected galaxies.

Based on counts observed from submm telescopes, *ISO* and *Spitzer*, a typical 33-mJy 215-μm pointing should detect 1.2 galaxies. Hence, to obtain the minimum reasonable statistical sample of order 20 galaxies at 215-μm, a minimum of 16 fields is probably required, drawn from a list with properties described below. (The test 31-mJy 155-μm single pointing from HAWC should detect about 0.5 galaxies serendipitously in addition to the known galaxy targeted in the GOODS-N field.)

We propose to target existing deep submillimeter-wave survey fields, preferably with available overlapping *HST* and *Spitzer* imaging and deep radio coverage. For example, SOFIA-HAWC pointings can be chosen within well-studied deep fields, such as GOODS, the Extended Groth Strip (EGS), Subaru deep field, COSMOS etc, choosing to target the brightest, most interesting SMGs known from existing surveys, and obtain their accurate far-IR SEDs.

SMGs behind rich clusters of galaxies (such as Abell 370 and 2218) can also be targeted: these have the advantage of strong gravitational lensing on arcmin scales for increasing the detectability of intrinsically faint background galaxies (see Fig. 3). The strongly magnified regions behind clusters at moderate redshifts have an extent comparable to the SOFIA-HAWC field of view, and they are thus excellent targets for single-field-of-view observations.

The non-cluster fields are much larger than the HAWC field of view, and so several HAWC pointings can be chosen within these fields. In the observing time list above we arbitrarily assign 4 6-hr 215-μm pointings to the equatorial Subaru deep field, COSMOS and GOODS-N fields (integration times of 24 hrs), and 1 155-μm 15 hr pointing to GOODS-N. Other fields satisfy these conditions, including GOODS-S. There may be operational constraints that favor northern or equatorial fields for deep extragalactic surveys, leaving southern flights free for studies of the Galactic center and inner disk. Note the location of both VLA and ALMA favors equatorial fields.

Special Requirements

There should be no special requirements, other than reasonably long integrations, for a HAWC deep survey project. Note that the observations can be broken into arbitrarily small subexposures. The final field choice will be better made as the legacy of the *Spitzer* missions deepest fields is available; however, a decision could be made now if necessary. These observations are time-critical in competition with other facilities, as – in its current form – HAWC cannot easily compete with the PACS and SPIRE instruments aboard *Herschel*. Developments to increase the size of the HAWC focal plane would increase its competitiveness.

Minimum obs time with same orientation:	0.5 hours
Maximum water:	low (but ETC implies not a huge effect)
RMS pointing jitter:	2.0 as

Precursor/Supporting Observations

Chosen target fields have existing mm/submm-wave imaging (from BOLOCAM, SHARC-II and SCUBA) and mid-IR observations from *Spitzer* that are deep enough to reach out to ultraluminous galaxies at high redshifts. Fields with these properties also routinely have follow-up near-IR and optical imaging of reasonable to excellent quality. We would like (and seek if unavailable) deep μJy radio images of the target fields to provide an extinction-independent, high-angular-resolution view of the fields.

After previously unknown far-IR galaxies with radio counterparts but no existing spectroscopic redshifts were found, redshifts would be sought using available optical, near-IR and submm photometric and spectroscopic techniques.