FIRST (HERSCHEL) IN THE CONTEXT OF CONTEMPORARY FACILITIES

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Abstract

FIRST has excellent capabilities for mapping and for high resolution spectroscopy in the heretofore largely unexplored region of the spectrum known as the Far-Infrared or submillimeter regime. In the wavelength range from about 80 μm to about 600 μm FIRST will have angular resolution as low as 6 arc sec (at 80 μm) and spectral resolution as low as 0.1 $\mathrm{km\,s^{-1}}$ (heterodyne). In L2 orbit, with a passively cooled 3.5 m primary mirror, FIRST will have great sensitivity and capability for both large area and deep surveying for nearby and distant objects. However, there will be very powerful contemporary intruments also operating in the same, or adjacent wavelength bands. It is important to discuss where these other instruments may compete with FIRST, either over a wavelength range, or for a particular science objective, and equally to find where FIRST is unique, or where it can perform a complementary function. Here we discuss the relative merits of FIRST, SIRTF, SOFIA and ALMA.

Key words: Galaxies: formation – Stars: formation – Missions: FIRST

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1. Introduction

It would be a daunting task to discuss the relative merits of all the millimeter, submillimeter and Far-Infrared instruments available to astronomy in the next decade. I therefore have constrained this article to a discussion of the most powerful, only. These are the space missions FIRST (Herschel) and SIRTF, the airborne mission SOFIA and the ground facility ALMA. I can only apologize for failing to discuss the undoubted major contributions which are being, or will be made by the space missions MAP, Planck, SWAS, ODIN, ASTRO-F, the many balloon instruments, and the ground-based facilities SMA, OVRO, BIMA, IRAM, CSO, JCMT, LMT, ASTRO, KOSMA, SEST, Quabbin, HHT and others yet to be named or currently changing ownership.... These facilities of course provide the data and astronomical results on which the FIRST mission is justified and around which it is planned, together with the earlier endeavors, IRAS, ISO and COBE. Probably the instrument with the greatest impact on FIRST, not discussed, is ASTRO-F. However, there is a talk specifically on ASTRO-F in the conference.

Table 1

MAJOR FIR/SUBMILLIMETER FACILITIES FOR THE 2000s

FACILITY	FIRST	SOFIA	SIRTF	ALMA
PLATFORM	SPACE L2	AIRBORNE	SPACE HELIOCENTRIC	HIGH MOUNTAIN
LAUNCH DATE	2007	2003	2002	2010
LIFETIME	3yrs	20yrs	2.5yrs	20yrs
WAVELENGTH (MICRONS)	600 - 60	600 - 1	160 - 3	1500 - 350
CLEAR TRANSMISSION	100%	60%	100%	30%
SPECTROSCOPY (Log R)	6, 3, 1	6, 3, 1	2	6
TELESCOPE (Dia - m)	3.5	2.5	0.85	12 X 64
TEMPERATURE (OPTICS)	80K	240K	5K	270K
EMISSIVITY	0.04	0.1	0.1	0.1

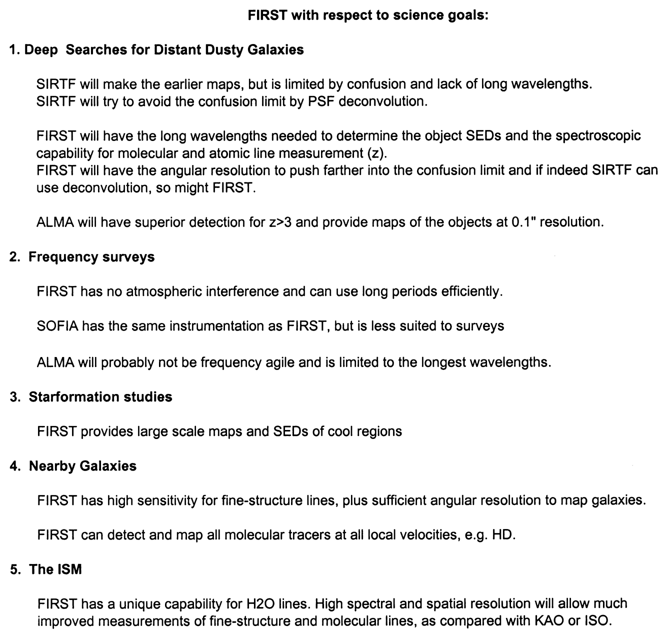
Returning to the selected comparisons, the data of Table 1. show the areas of strength and weakness for the four projects. Some of the data in Table 1. may be out of date already, e.g., SOFIA has suffered a two year slip. The strength of FIRST is the wavelength coverage through the whole submillimeter/FIR band and the ability to perform large scale surveys for distant dusty galaxies, with high spatial resolution, giving a lower confusion limit. For spectroscopy, FIRST has almost continuous very high spectral resolution coverage of the submm/FIR, much of which is not available from the ground. The L2 orbit provides a favorable thermal environment, resulting in moderately low backgrounds for the detectors. The low emissivity is also important in this respect. SOFIA also covers some significant fraction of the summ/FIR, but there is considerable residual atmospheric absorption and a higher telescope optics temperature, which inhibits full spectral coverage and makes both spatial and spectral surveys difficult. However, SOFIA has the advantage that the detectors can be upgraded as development proceeds. SIRTF has very high sensitivity for dust emission and will produce large and sensitive surveys for distant galaxies, limited only by confusion. However, such surveys will be at shorter wavelengths than for FIRST and so will be sensitive to objects at lower z values. SIRTF has no medium or high spectral resolution capability. SIRTF will be the first of the new generation of submm/FIR instruments to operate and will provide large numbers of interesting objects for FIRST to

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

follow-up in terms of SED determination and high spectral resolution study of atomic and molecular lines. ALMA will operate only at the longer wavelengths, as limited by the atmospheric transmission. It will have extremely high spatial resolution and will determine the absolute positions and morphology of the SIRTF and FIRST survey objects. It will be the best instrument for detecting very high z objects, if they exist.

Table 2 itemizes some of the broadly defined areas where FIRST will have a unique or particularly important roles to play.

Table 2



FIRST with respect to science goals:

1. Deep Searches for Distant Dusty Galaxies

SIRTF will make the earlier maps, but is limited by confusion and lack of long wavelengths.
SIRTF will try to avoid the confusion limit by PSF deconvolution.

FIRST will have the long wavelengths needed to determine the object SEDs and the spectroscopic capability for molecular and atomic line measurement (z).
FIRST will have the angular resolution to push farther into the confusion limit and if indeed SIRTF can use deconvolution, so might FIRST.

ALMA will have superior detection for z>3 and provide maps of the objects at 0.1" resolution.

2. Frequency surveys

FIRST has no atmospheric interference and can use long periods efficiently.

SOFIA has the same instrumentation as FIRST, but is less suited to surveys

ALMA will probably not be frequency agile and is limited to the longest wavelengths.

3. Starformation studies

FIRST provides large scale maps and SEDs of cool regions

4. Nearby Galaxies

FIRST has high sensitivity for fine-structure lines, plus sufficient angular resolution to map galaxies.

FIRST can detect and map all molecular tracers at all local velocities, e.g. HD.

5. The ISM

FIRST has a unique capability for H2O lines. High spectral and spatial resolution will allow much improved measurements of fine-structure and molecular lines, as compared with KAO or ISO.

2. ANGULAR RESOLUTION

Angular resolution is determined, for diffraction limited telescopes, by the telescope primary mirror diameter. This is true, provided the telescope mirror has a mechanical surface accuracy of $\lambda/20$ (rms) or better. Since the shortest operating wavelength for FIRST is 60 μm, the required surface accuracy is about 3 μm. Almost certainly FIRST will achieve this, so a simple, direct comparison with SOFIA and SIRTF can be made. The angular resolution is particularly important for the confusion limit and for the detection capability for small objects.

Figure 1 shows the angular resolutions, as a function of wavelength, for a variety of submm/FIR telescopes. FIRST is superior, with a best resolution of about 6″. The advantage in effective telescope area is about 2 over SOFIA and 17 over SIRTF. Also shown (after the SOFIA web page) are curves for ISO, KAO and IRAS. It is harder to make a comparison with ALMA, which would have a resolution limited by phase stability. Roughly it might be expected that ALMA would be able to make maps at 0.1″ resolution. So at wavelengths where it can operate, ALMA is by far the best spatial structure discriminator.

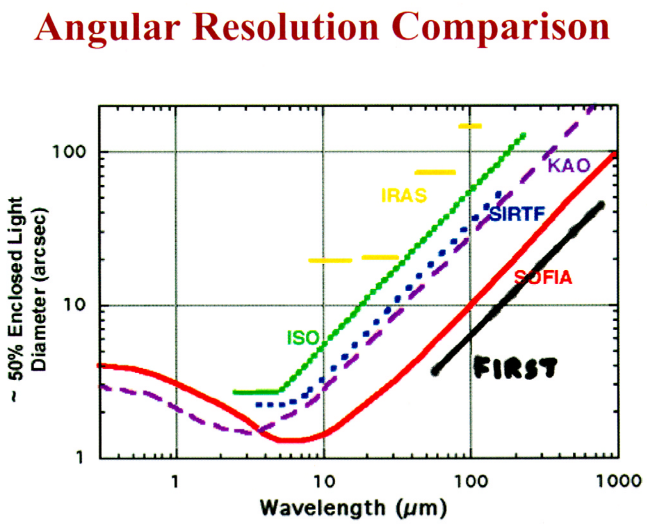


Figure 1. A comparison of angular resolution (after the SOFIA web site).

3. SENSITIVITY

Sensitivity to the continuum emission from a point source is measured in mJy. We have also to specify the number of sigma and the integration time. A comparison between instruments would then depend on telescope area, background radiation, detector noise and quantum efficiency etc.. This would be reasonably straightforward except that the more sensitive systems reach a limit determined by structure in the sky background and known as confusion. The confusion may be due to foreground dust clouds in our galaxy or distant galaxies of low emission strength. The effect of confusion is twofold. When making a LogN-LogS plot the number counts are reduced by loss of discrimination, but also the intensities are reduced by the contribution of the sky background to the system noise level, so raising the apparent zero level. Thus the effect of confusion depends on the number of objects in the various intensity ranges, which is not known in many cases. A further difficulty is where to set the limit of reliability, so as not to suffer the effects of confusion, since this will depend on the probably unknown LogN-LogS curve. A common choice is one detected object per 20 beams. Figure 2 shows the sensitivity comparison for FIRST, SOFIA and SIRTF, as a 1σ result for one hour integration. The low thermal background for SIRTF means that SIRTF will be very sensitive and quickly integrate down to the confusion limit. FIRST and SOFIA, with larger telescopes, have lower confusion limits, but take longer to reach the confusion limits.

In the FIRST wavelength range, on the plot of Figure 2, FIRST is the most sensitive, because of the low

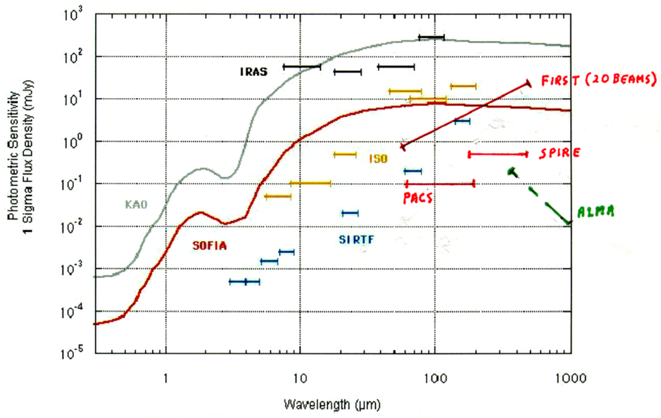


Figure 2. A comparison of sensitivities (after SOFIA web site). See text for a discussion of confusion.

confusion limit and the relatively low thermal background. The horizontal bars for PACS and SPIRE represent the background one sigma noise in one hour. Clearly FIRST can easily reach the 20 beam confusion limit, but will not reach the 1σ confusion limit. One can ask what it means to integrate below the 20 beam limit, where there are errors developed on both the number and intensity axes. It then becomes an investigation of the weak underlying sources and one can contemplate deconvolution techniques for high signal to noise cases (Reike, Young and Gautier, 1997).

At the longest wavelengths ALMA is the most sensitive and has no confusion limit, because the resolution of $0.1''$ or so should actually resolve the individual objects. Thus, all questions concerning apparently confused fields will eventually be answered by ALMA.

If the question to be answered is "What is the likely discovery rate for distant dusty objects for a given instrument", the answer is given by the plot in Figure 3 (Blain, 2000). Here, all instruments are treated equally in terms of confusion limit. Remarkably, the best cases show detection rates more than 100 times that of SCUBA. The highest detection rates are with SIRTF at 160 μm and SPIRE at 250 μm, both for 100 mJy sources. However, SPIRE has the better results for 10 mJy sources, since SIRTF has run into the confusion limit (the left-hand ends of the curves represent the confusion limits). PACS at 170 μm is not quite as fast as SIRTF, but is effective for much weaker sources, as low as 2 mJy.

4. ATMOPSHERIC TRANSMISSION

The submillimeter part of the electromagnetic spectrum has been slow to develop, particularly for astrophysical applications. One of the primary factors has been the poor transparency of the Earth's atmosphere. The major culprit is the water molecule, which not only blocks our view of water in the ISM, but also blocks most of the rest of the spectrum, at least from the ground. This has forced the use of high mountain sites, airplanes, balloons and, ultimately, space. Since SOFIA and ALMA are competitive, contemporary instruments, we need to examine the atmospheric transparency for each, to understand the regime unique to FIRST.

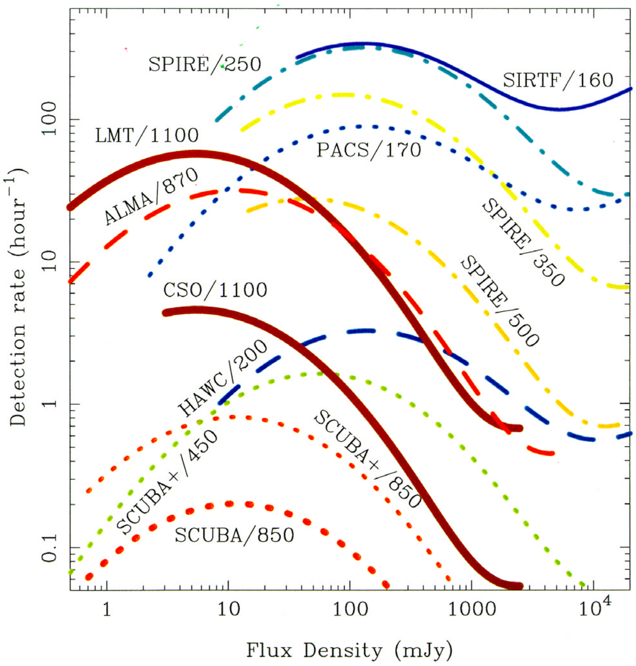


Figure 3. A comparison of distant dusty object detection rates for space, airborne and ground facilities (Blain, 2000).

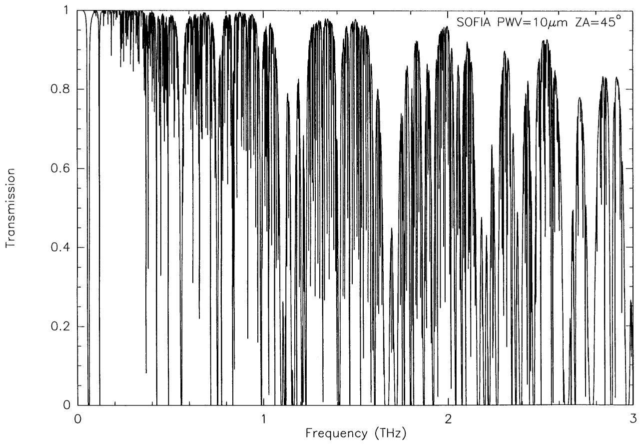


Figure 4. The atmospheric transparency for SOFIA.

The transparency for SOFIA is plotted in Figure 4. For continuum observations the loss of transmission is relatively small, mostly in the 10-20% range, but this translates to a large contribution to the background seen by the detectors. For spectroscopy, depending on the criterion used, about 40% of frequency space is adversely affected, such as to make a line survey difficult or impractical. It also will not be practical to observe all galaxies in a given spectroscopic line, since the redshift range will be limited, even if the rest frequency is transparent. So, although SOFIA will be able to observe a considerable fraction of the submillimeter frequency space, many important species, including water of course, will be the province of FIRST. Certainly FIRST will be unique in its ability to make complete line surveys.

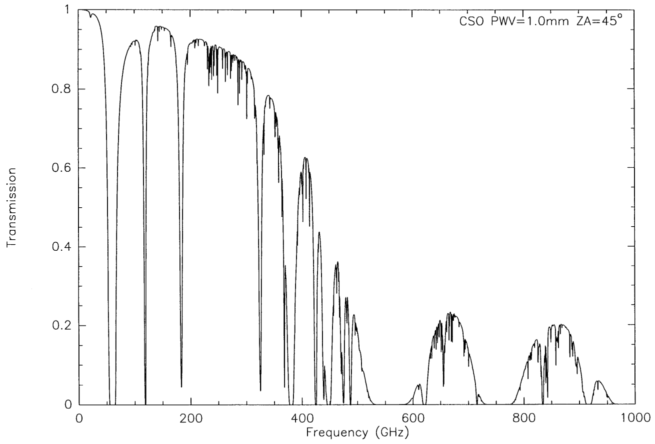


Figure 5. The atmospheric transparency for ALMA in average weather.

ALMA is a most powerful aperture synthesis instrument, providing very high sensitivity in the 2 mm – 350 μm range. It is however limited by the transmission of the Earth's atmosphere, as seen in Figure 5. The effect of the relatively narrow bands in which ALMA is forced to work, is to limit the number of submillimeter lines to be observed and to limit line surveys. Also, due to the increasing absorption with frequency, the sensitivity rapidly degrades at the shorter wavelengths. This is seen in Figure 2, where the ALMA behaves very differently from the other instruments. Part of this is due to the increasing receiver noise with frequency.

5. High Resolution Spectroscopy

HIFI is a heterodyne spectrometer on FIRST, designed to cover most of the spectrum from about 480 GHz to 1900 GHz, contiguously. There is a gap between about 1250 and 1400 GHz which is not covered in the baseline plan. The almost continuous high resolution spectroscopic coverage with low noise receivers is designed to support line surveys - a forte of FIRST - from the groundstate fine-structure line of atomic carbon at 492 GHz [CI], to the groundstate fine-structure line of ionized carbon at 1900 GHz [CII].

An example of a line survey taken in a partially transparent window (see Figure 5) with the CSO is shown in Figure 6. There are about a thousand lines in this "Molecular line forest", which is just a small fraction (8%) of the HIFI band. Besides the prolific molecular and chemical information carried in the spectrum, there is a wealth of excitation and kinematic information as seen in the inserted "Blow-up" panels. A detailed description of the scientific features of line surveys is to be found in the article in this proceedings by Ewine VanDishoeck (2000).

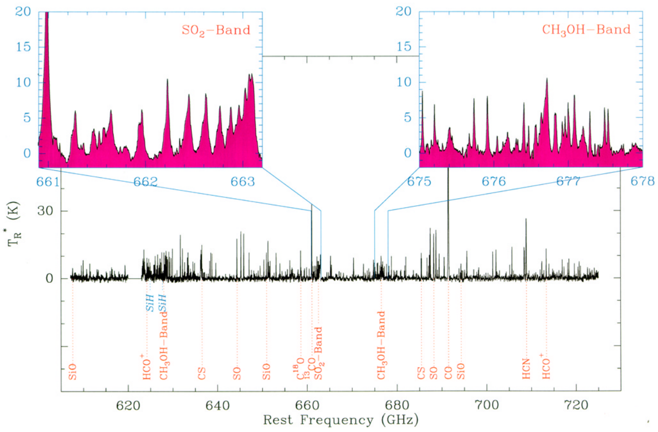


Figure 6. A part of the "Molecular Line Forest" observable from the CSO (Schilke et al. 2001).

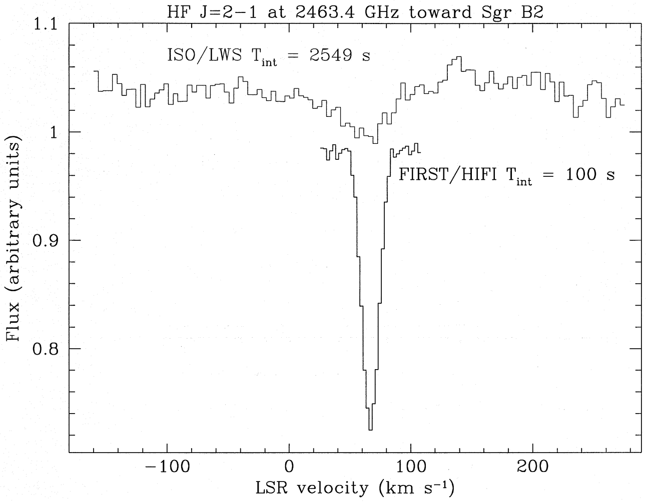


Figure 7. ISO detection of HF (Neufeld et al. 1999) as it would be seen with a heterodyne spectrometer on FIRST.

Besides line surveys, HIFI will support individual line studies, or individual molecule studies, e.g. water. An example of the power of high resolution spectroscopy is presented in Figure 7. The detection by ISO of the HF molecule is shown in the upper scan (Neufeld et al, 1997). It is seen in absorption against SgrB2. The lower scan represents the HIFI spectrum which could be obtained in about 1/25th of the integration time. The improvement over ISO is partly the effect of the bigger telescope and partly the more sensitive detectors and higher spectral resolution. Although the frequency of this HF (J=1–2) line lies outside of the present HIFI spectral range, the J=0–1 line will be accessible and will be even more easily detected.

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