Laboratory Astrophysics Needs of the Herschel Space Observatory

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Abstract

The science teams of the Herschel Space Observatory have identified a number of areas where laboratory study is required for proper interpretation of Herschel observational data. The most critical is the collection and compilation of laboratory data on spectral line frequencies, transition probabilities and energy levels for the known astrophysical atomic and molecular species in 670 to 57 micron wavelength range of Herschel. The second most critical need is the compilation of collisional excitation cross sections for the species known to dominate the energy balance in the ISM and the temperature dependent chemical reaction rates. On the theoretical front, chemical and radiative transfer models need to be prepared in advance to assess calibration and identify instrument anomalies. In the next few years there will be a need to incorporate spectroscopists and theoretical chemists into teams of astronomers so that the spectroscopic surveys planned can be properly calibrated and rapidly interpreted once the data becomes available.

The science teams have also noted that the enormous prospects for molecular discovery will be greatly handicapped by the nearly complete lack of spectroscopic data for anything not already well known in the ISM. As a minimum, molecular species predicted to exist by chemical models should be subjected to detailed laboratory study to ensure conclusive detections. This has the greatest impact on any astrobiology program that might be proposed for Herschel. Without a significant amount of laboratory work in the very near future Herschel will not be prepared for many planned observations, much less addressing the open questions in molecular astrophysics.

1. Introduction

The Herschel Space Observatory is a far infrared observatory class mission scheduled for Ariane 5 launch in 2007. The observatory will reside at the second Lagrange point L2, where it is easy to shield the spacecraft from the sun as well as the Earth and Moon. The L2 environment allows for passive cooling of the cryostat shell and telescope on Herschel to below 80 Kelvin. The Herschel mission has three instrument mounted in a 2500 liter superfluid helium cryostat with helium vapor cooling providing temperature levels of approximately 4K and 15K. The silicon carbide telescope will be diffraction limited at 60 microns and have a 3.5 meter aperture. The nominal Herschel mission is for three years with a design goal of 5 years. Each instrument will be operated separately during observations. Two thirds of the observational time will be open time subject to a proposal process fully open to American and European observers.

The Herschel mission supports three instruments; the Photodetector Array Camera and Spectrometer (PACS), the Spectral and Photometric Imaging Receiver (SPIRE) and the Heterodyne Instrument for Far Infrared (HIFI). PACS is designed to perform two color imaging photometry in the 57-210 micron band or broadband spectroscopy with a grating spectrometer on two arrays of detectors at a resolution $\lambda/\Delta\lambda$ of approximately 1000. SPIRE is designed to perform three-color imaging photometry or broadband Fourier transform spectroscopy with at a resolution $\lambda/\Delta\lambda$ of 20-1000. HIFI is a seven channel dual polarization single pixel heterodyne receiver with 4 GHz of intermediate frequency bandwidth within each polarization in the 480-1250 or 1410-1910 GHz frequency range.

The Herschel Space Observatory is the first facility to cover the entire far infrared region and the only mission covering the 200-600 micron spectral range. The L2 environment provides a complete lack of atmospheric absorption and emission in a much lower thermal background environment than possible on the Earth.

2. Instruments and Science Objectives

The PACS instrument is designed to have a relatively large 1.75 by 2.5 field of view in photometry or a 50 by 50 field of view for spectroscopy. The PACS science program is focused on galaxies, with major observing programs planned for large area extragalactic surveys and follow up spectroscopy of distant galaxies. In our local galaxy, PACS will explore the initial mass function of cores and clusters as well as study HD and the galactic distribution of the D/H ratio as a probe of galactic evolution.

The SPIRE instrument, like PACS, is optimized to have a large field of view, 4 by 8 arcminutes in photometry and greater than 2 arcminutes for spectroscopy. The SPIRE science programs main target is also galaxies, with the major observing programs planned for large area extragalactic surveys. SPIRE will also perform spectroscopy of distant galaxies. In our local galaxy, SPIRE will explore the initial mass function of cores, clusters and star forming regions. Since SPIRE and PACS overlap very little in wavelength space, it is anticipated that the deep extragalatic surveys will be a joint science program with the 5 (or 6) available colors providing a great deal of spectral energy distribution information without further spectroscopy.

The HIFI instrument is optimized to return high R to 10^7 spectral data. As such HIFI is optimized to study the details of Doppler shifts, resolve close velocity groups, and perform complete chemical and dynamical inventories. The HIFI science program is divided into two key programs requiring large chunks of observing time and a number of topical core programs. The identified key programs are to perform complete spectral surveys of a significant number of objects (~30) and to study in detail the role of water in the universe. The core science programs are to study the interstellar medium in the Milky Way, the late stages of stellar evolution, solar system objects (several will probably be part of the spectral survey program), the interstellar medium in galaxies and star formation.

3. Instrument Laboratory Needs

The PACS instrument is optimized to study spectral energy distributions as well as strong Doppler broadened lines. As a result, the major laboratory needs are in the areas of Calibration sources, dust properties and models and radiative transfer models for complex sources. On orbit calibration of PACS requires a variety of continuum sources with a wide range of well-known flux levels in the 57-210 micron range. Spectroscopic frequency calibration requires the frequencies of bright emission lines. Pointing calibration requires bright stars in the far infrared with well-known astrometric positions. Proper interpretation of PACS data will require detailed models and measurements of dust spectral energy distributions as a function of chemical composition and conditions. Additionally, dust extinction as a function of conditions is also needed for the study of complex sources. Lastly full analysis of PACS data and early detection of instrument problems will require complete and tested radiative transfer models of complex sources. These models must include gas, dust and 3-D morphology and be robust enough to cope with only a few lines and a continuum for distant object studies.

Since the SPIRE instrument is optimized to study spectral energy distributions as well as strong Doppler broadened lines, the laboratory needs are similar to PACS. However, SPIRE is really the first imaging instrument in the majority of its spectral range. Due to SPIRE new wavelength range the major laboratory need is in the areas of Calibration sources. SPIRE requires sources with known and modeled spectral energy distributions. SPIRE also needs a very precise model of Neptune and precise models of a number of asteroids in the 680-200 micron range. SPIRE also needs far infrared models of bright stars and a number of point-like objects in the 18 beam. Calibration sources are needed, which cover the entire dynamic range, are non-variable and distributed throughout the sky. For spectroscopic calibration sources with known low continuum levels, sources with known or well modeled line fluxes, which are non-variable, point like and have several observable non-blended lines. The line sources need to be distributed around the sky and cover the SPIRE dynamic range. For the proper interpretation of SPIRE data, good models of galaxy spectral energy distributions are needs as well detailed models and measurements of dust spectral energy distributions as a function of chemical composition and conditions. Additionally, dust extinction, as a function of conditions is also needed for the study of complex sources. Additionally, complete and tested radiative transfer models of complex sources. These models must include gas, dust and 3-D morphology and be robust enough to cope with only a few lines and a continuum for distant object studies.

The high spectral resolution, wide spectral coverage and high frequency of HIFI make it an enormous challenge for laboratory astrophysics. HIFI will return an enormous amount of highly detailed data, which will require several levels of laboratory data for analysis and finally interpretation. The basic analysis of HIFI data requires that the observed features be assigned to a transition in absorption or emission of an atom or molecule. For this to happen, the transition frequencies of all potential atoms and molecules must be known to better than HIFIs resolution. At a minimum this requires the rotational and low lying ro-vibrational spectra of all the known ISM molecular species be known and cataloged for use. Additionally the main isotopomers of ISM species must be known and cataloged for use. To take full advantage of HIFI, the transitions of potential molecules must be recorded and cataloged. All this must happen in the 480-1910 GHz frequency range. The next level of spectral data requires the transition strengths be precisely known. At this point the raw HIFI data is ready for interpretation, but interpretation requires several more layers of laboratory data.

Full interpretation of HIFI data requires collisional excitation parameters for each observed line, chemical reaction rates for all species related to those observed, chemical models including grain effects, detailed radiative transfer models including line transport and physical conditions. In the case of water, state-to-state excitation parameters are also necessary along with ratiative transfer models with simultaneous solution of statistical equilibrium and line transfer in the comoving frame including temperature, density and velocity gradients. The chemical reaction rates for gas phase, gas-dust, and on dust grain and collisional rates must also be cataloged in an easy to use format.

3.1. Laboratory Prospects

The Herschel space observatory represents a major challenge to the laboratory astrophysics community. Basic data such as the needed line intensities data can quickly exceed the current boundaries of fundamental physical knowledge. Similar problems arise in chemical data, chemical models, excitation cross sections, radiative transfer models and dust studies. Data catalogs only exist for reaction rates and spectral lines, however they are not close to comprehensive or complete. No catalog exists for excitation or dust chemistry. Astrophysics has in the past leveraged the state of the art chemical research techniques for long wave length astronomy. Unfortunately, the data now required for astrophysics is generally not at the cutting edge of chemical research funded by other interests, so astrophysics will have to support the programs it needs to interpret astrophysics data. The problem will further compound itself, since graduate programs and students currently have no incentive or long term prospects if they study in the areas of laboratory astrophysics. The problem is not unique to Herschel or long wavelengths and generally is shared by a number of missions so no one mission feels compelled (or is given the resources) needed to generate the required data. In the case of Herschel, responsibility for a laboratory program could just as easily be assigned to SOFIA or in many cases SIRTF or SWAS. As a result, a laboratory program is the responsibility of none. NASA, ESA, and a variety of national agencies in Europe are going to spend in excess of $1.5 billion for Herschel, but there is no specific budget or plan for performing the basic lab work necessary. The lack of a lab program is a major risk to the Herschel science return, because instrument anomalies will take longer to discover and correct, calibration will be problematic and will take more observing time, and complete interpretation of the data will not be possible, undermining the science. An identical statement could just as easily be made about a number of other astronomy instruments. None of this would be necessary with a proper lab program.

4. Conclusions

A number of steps urgently need to be taken prior to launch of Herschel. These include funding of basic laboratory and theoretical studies of line frequencies, transition moments, and collisional excitation cross sections. Chemical and radiative transfer models need to be prepared in advance and tested with ground based observations. Comprehensive catalogs of line frequencies, intensities, excitation cross sections, and temperature dependent chemical reaction rates need to be prepared. A comprehensive ground based program for calibration needs to established and funded, since no time allocation committee would normally grant proposals for calibration studies. NASA astrophysics has three choices in addressing Herschels lab needs. The existence of a lab data problem can be denied until after Herschel produces data, which defies scientific interpretation. The Herschel mission could be funded directly for lab support, or NASA could establish and fund a proper, focused lab program across missions. In theory, the current NASA system is designed for the latter, but in reality it is forever addressing data needs after the observations. In the case of Herschel the lab burden is shared with Europe, but it is not entirely Europe's burden either and NASA must contribute.

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.