National Aeronautics and Space Administration
Ames Research Center

Stratospheric Observatory for Infrared Astronomy

SOFIA Stratospheric Observatory for Infrared Astronomy

SOFIA and Laboratory Astrophysics
&
European Plans: Molecular Universe

Xander Tielens, SOFIA Project Scientist

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OVERVIEW OF SOFIA

SOFIA Stratospheric Observatory for Infrared Astronomy

- SOFIA is 2.5 m telescope in a modified B747-SP aircraft
- Joint Program between the US (80%) and Germany (20%)
- Optimized for far-infrared and submillimeter observations
  - 9 first generation science instruments
  - Instruments will be changed and upgraded over lifetime
  - Designed for 20 year lifetime
  - Operated from Moffett Field, CA
  - Deployments
  - >120 flights per year of ~8 hrs
  - Build on KAO Heritage
- Nearly all observing time is for GOs - annual cycle
- Hands-on training for future scientists and icon for education and public outreach

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SOFIA STATUS

SOFIA Stratospheric Observatory for Infrared Astronomy

- SORT team has reviewed SOFIA
  - No insurmountable technical or programmatic challenges
- SOFIA has been reinstated in the NASA budget for 2007
- SOFIA will be baselined at the Agency PMC, Nov 1, 2006
- SOFIA Science Operation Review February 2007
- Structural modifications complete !
- First flight: early 2007
- Followed by ferry to Dryden
- Early science phase: Initial Operational Capability: early 2010

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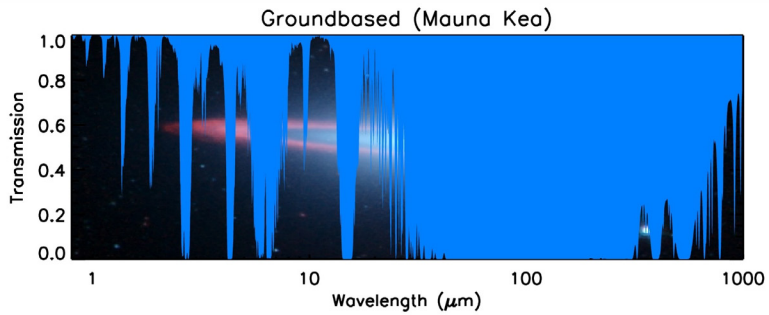
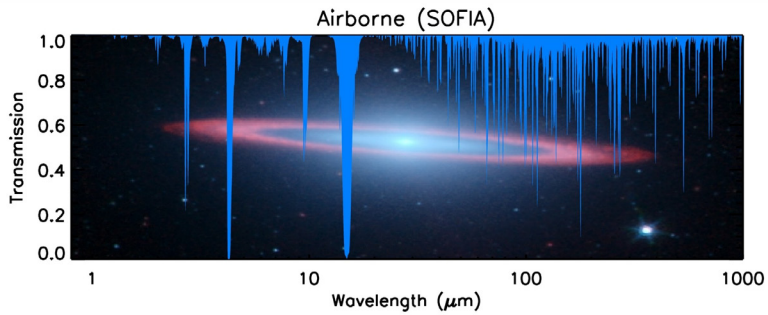
AIRBORNE ASTRONOMY





- SOFIA flies above the tropopause - above 99.9% of the water vapor in the atmosphere - thereby opening up the IR universe
- SOFIA is a near-space observatory that comes home after every flight and coupled with a long life time this enables:
  - Wide instrument complement and fast change out
  - Larger and more complex instrumentation than space-based platforms
  - Rapid instrument upgrades
  - Rapid incorporation of new, cutting-edge technology
  - Test bed for future space instrumentation
  - Training ground for young experimentalists

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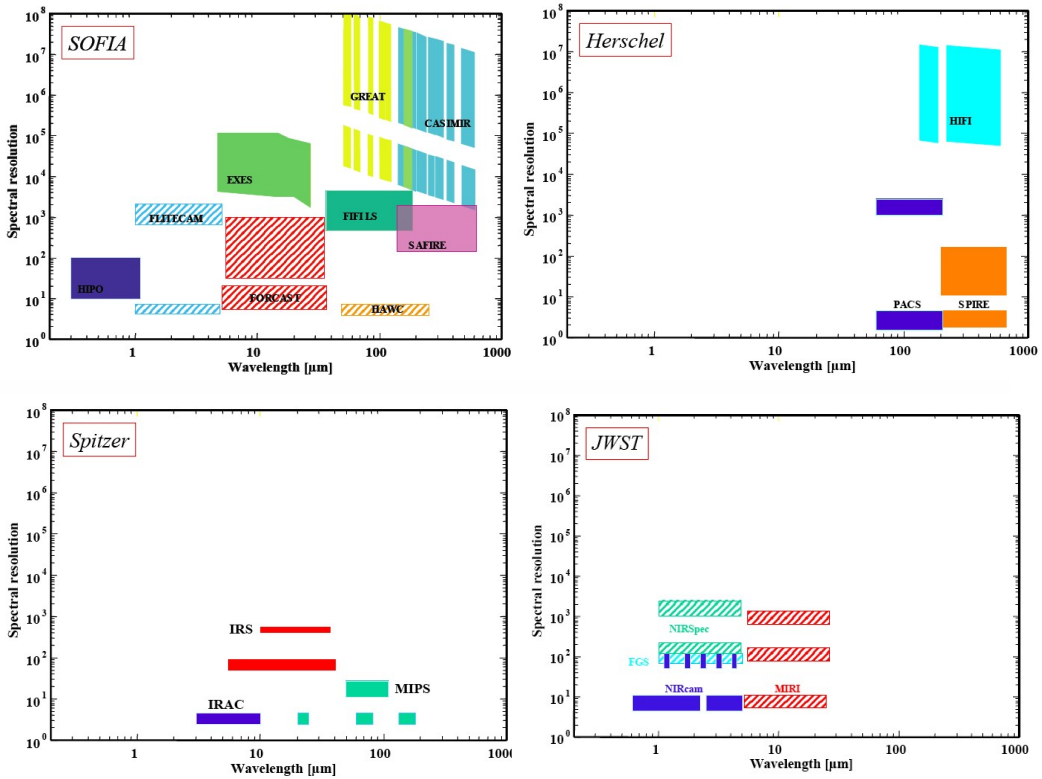
IR MISSIONS

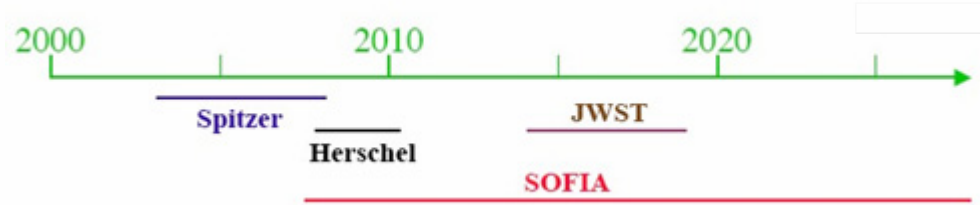
SOFIA Stratospheric Observatory for Infrared Astronomy

As an airborne mission, SOFIA has a unique wide instrument suite

- SOFIA covers the full IR range with imagers and low, moderate, and high resolution spectrographs
- SOFIA complements the wavelength ranges and spectral capabilities of other space missions over the designed 20 year lifetime
- SOFIA can take fully advantage of improvements in instrument technology



Mission operations timeline



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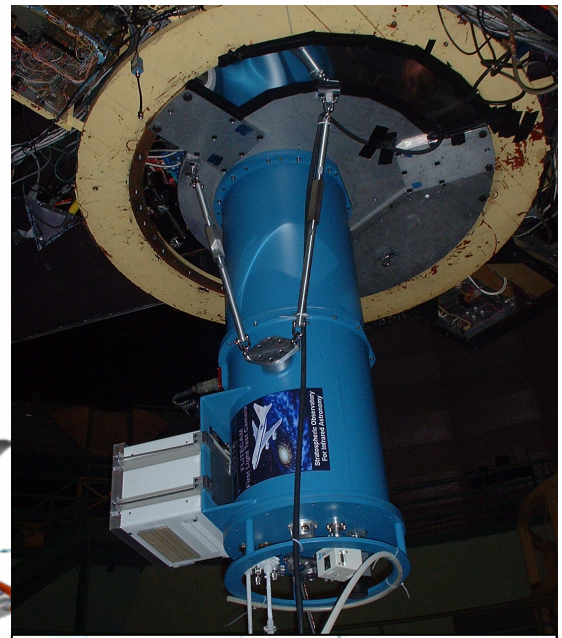
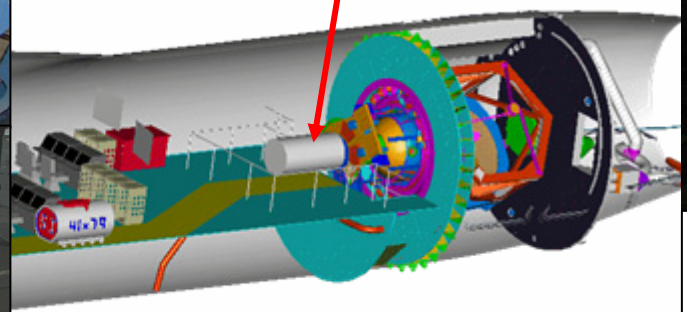
The Four Science Instruments at IOC

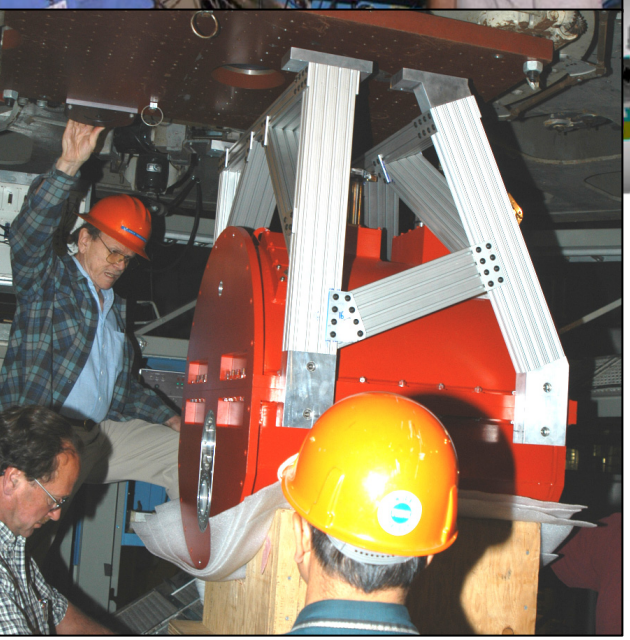
Working/complete HIPO instrument in Waco on SOFIA in Aug 2004

Working/complete FLITECAM instrument at Lick in 2004/5



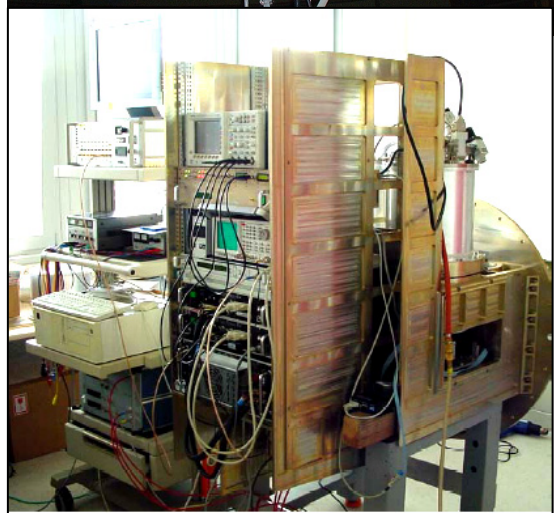
Science Instrument





Working FORCAST instrument at Palomar in 2005

Successful lab demonstration of the German instrument GREAT in July 2005



Lab-picture of GREAT equipped with the KOSMA 1.9THz channel

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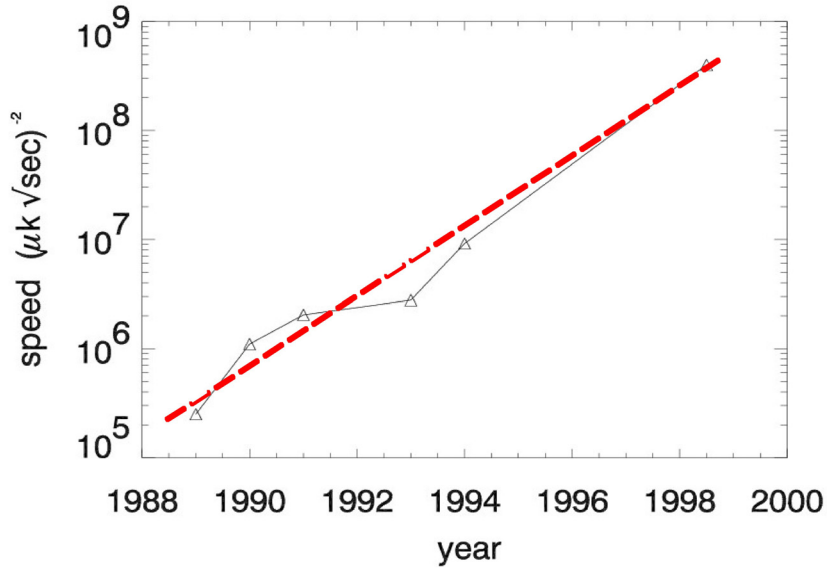
FUTURE INSTRUMENTATION



- Technology advances rapidly in the far infrared due to increases in sensitivity and detector array sizes and we can expect a factor 10 increase in observing "speed" every 5 years
- As an airborne program, SOFIA has a major instrumentation component with a planned major upgrade of an existing instrument or a new instrument every year at a cost of ~$7 million/year
- Thus, SOFIA evolves into a completely new mission in ~5 yr at only the low cost of the instrument development program

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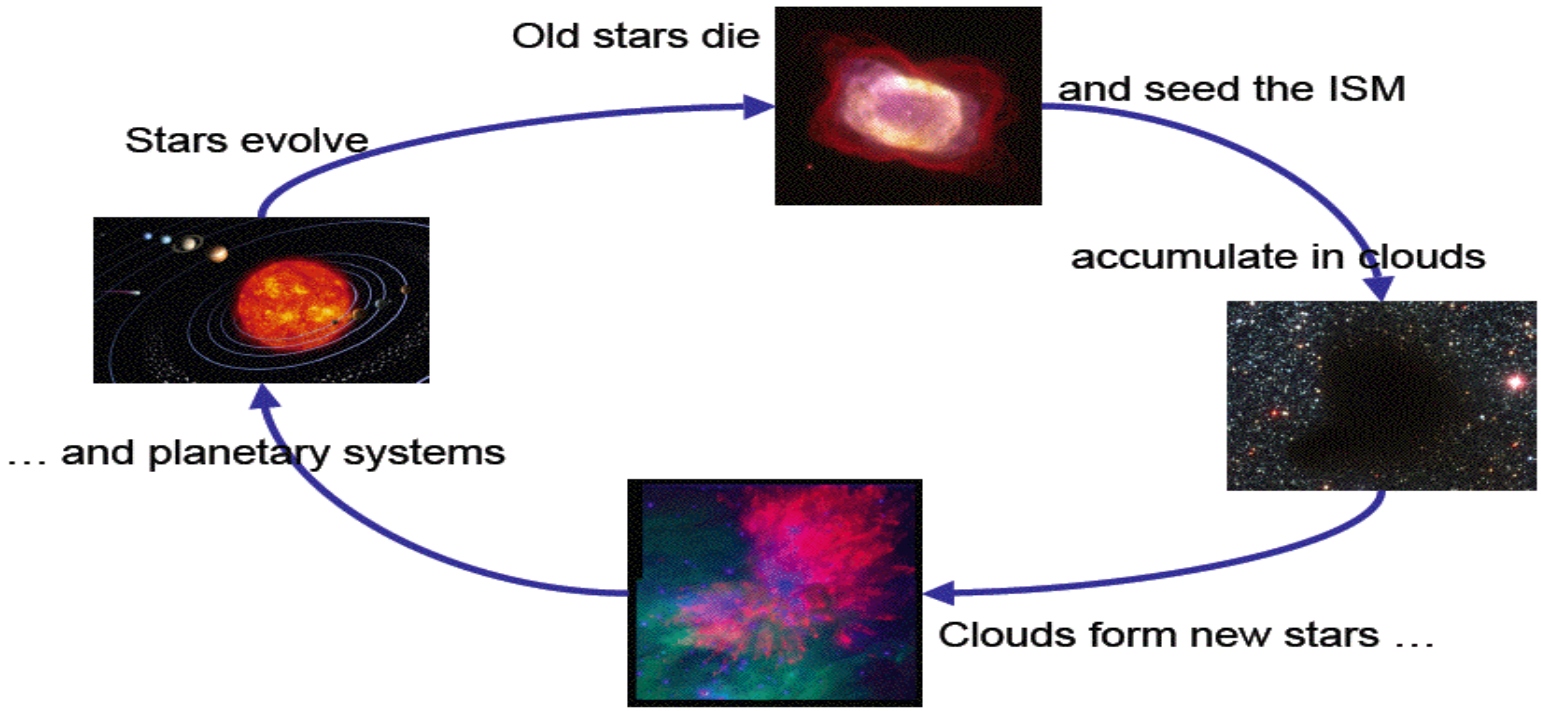
LIFECYCLE OF GALAXIES



SOFIA's science

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SCIENCE VISION

SOFIA Stratospheric Observatory for Infrared Astronomy

SOFIA addresses key science questions in unique ways:

- How does matter in the interstellar medium of galaxies accumulate to form stars (like the Sun) and their planets (like the Earth) ?
- How do stars die, how do they enrich the interstellar medium of galaxies with newly nucleosynthesized elements, and what becomes of these ashes once returned to the interstellar medium ?
- What are the properties of the newly-discovered planet-like objects on the outskirts of our solar system (their sizes? composition ? presence of moons ? atmospheres ?), and what does that tell us about how our solar system formed ?
- Were some of the organic molecules needed for life on Earth created in space and are they present in other planetary systems that are now forming ?
- What powers ultraluminous galaxies, what is the energetic interplay of star formation processes and black hole activity in these galaxies, and what does that tell us about the evolution of galaxies over the history of the universe ?
- What is happening near the enormous black hole in the center of our own galaxy and what does that teach us about the origin and evolution of black holes ?

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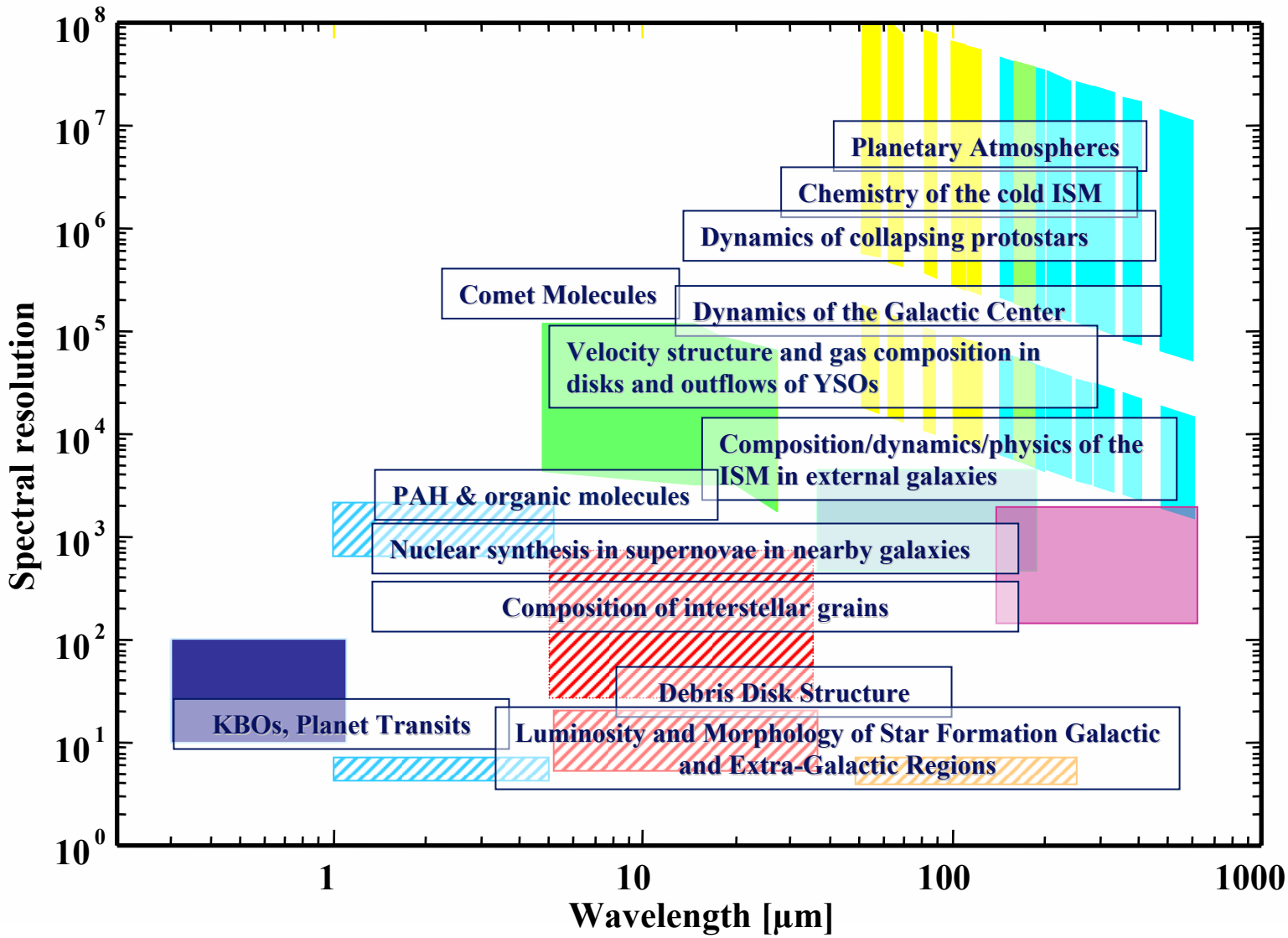
Spectral coverage enables SOFIA to study at the optimum wavelengths and resolution many phenomena….

SOFIA Stratospheric Observatory for Infrared Astronomy



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STAR AND PLANET FORMATION

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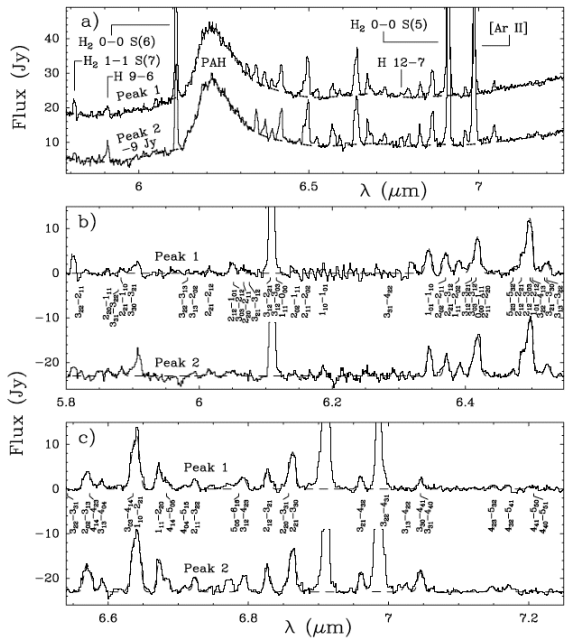
SOFIA will study the molecular composition of regions of star and planet formation

Spectroscopy reveals the presence of water, simple hydrocarbon molecules, and complex nitrogen-bearing organics in regions of star formation



SOFIA's high resolution spectrographs are unique for precisely identifying organic and pre-biotic molecules, determining their abundances, and identifying chemical routes and thus to uniquely address:

- What is the organic inventory of newly forming planetary systems ?
- What is the distribution of water, where is the "snow-line" in newly forming planetary systems ?

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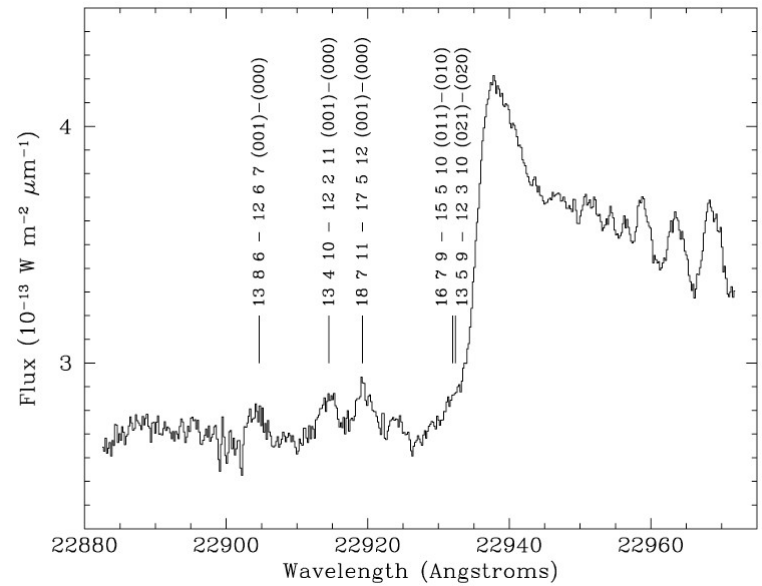
Hot Water in SVS 13

- K band spectrum
- Emission lines due to H_2O
- Identification and analysis based upon sunspot spectrum and QM calculations
- Results:
  - T ~ 1500 K
  - Inner (<0.3 AU) disk
  - H_2O abundance decreased by a factor 10 relative to CO
- EXES on SOFIA will be able to probe the ν_2 mode and thus gas at temperatures 100-600 K and 1-3 AU



Carr et al. 2004, ApJ, 603, 213

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Molecular Complexity

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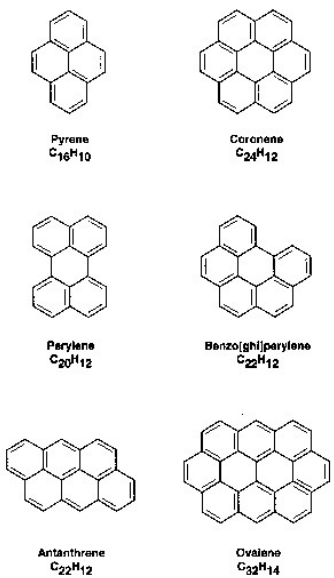
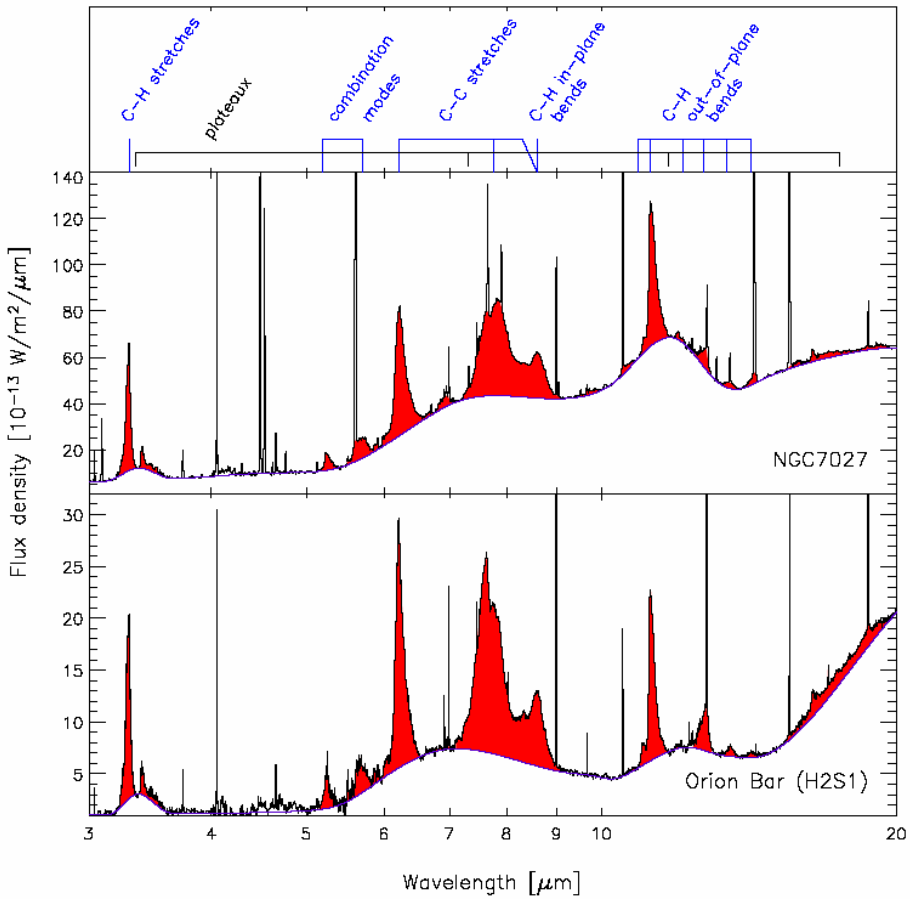
Characteristics of interstellar PAHs

- A multitude of bands due to vibrational modes of PAHs
- Molecular species with ~50 C-atoms
- Total abundance ~10^{-5} relative to H
- ~4% of elemental C





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LARGE MOLECULES ARE EVERYWHERE

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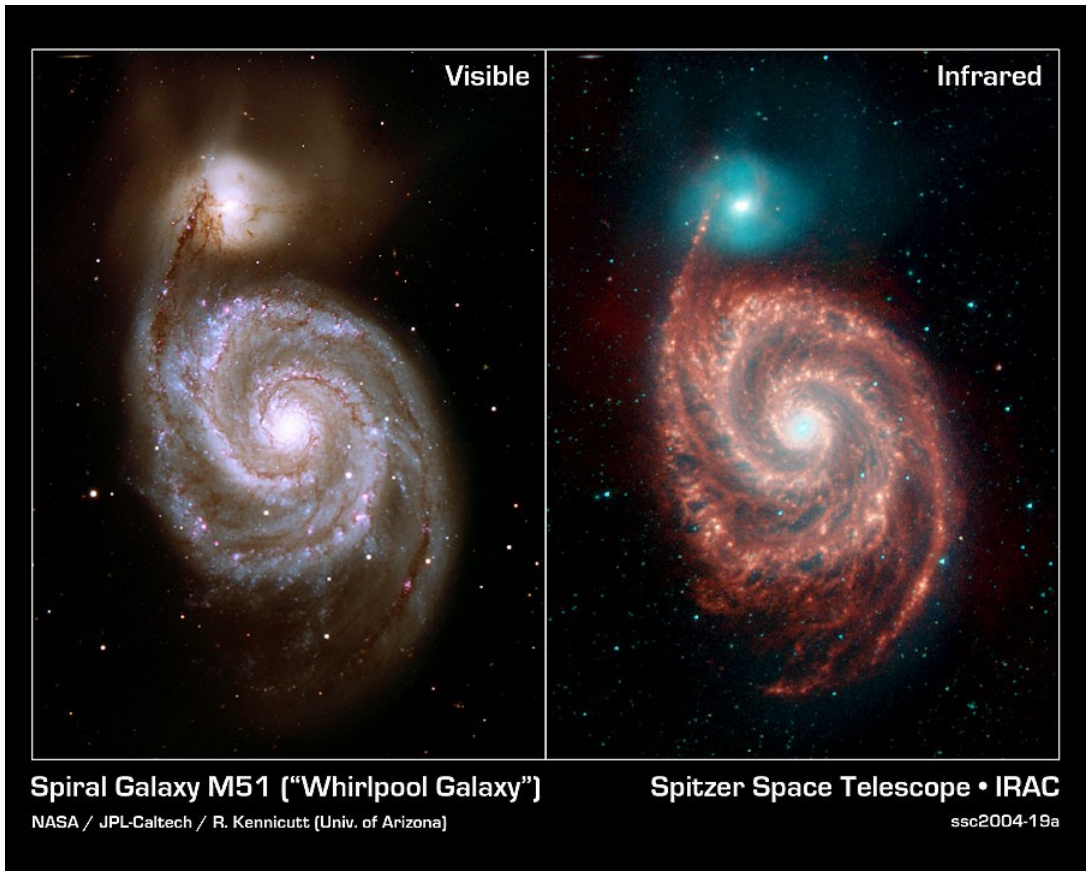

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MOLECULAR COMPLEXITY

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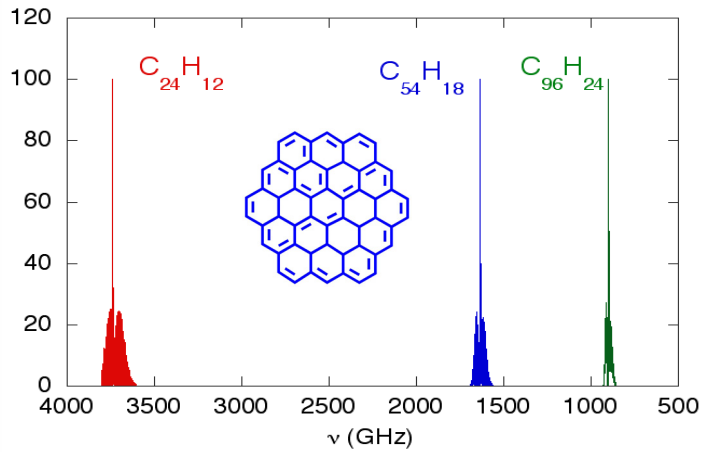
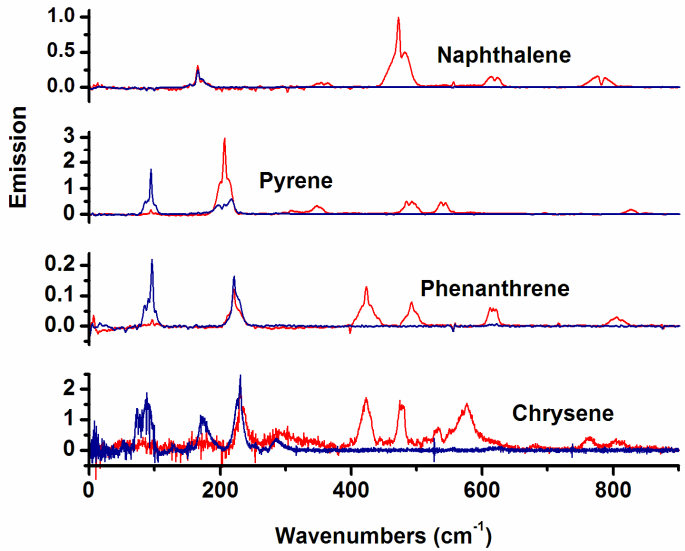
- What is the molecular inventory of space ?
- What processes dominate interstellar chemistry ?
- How complex can the molecular universe be ?
- What is the role of interstellar molecules in the inventory of newly formed planetary systems ?
- What is the role of interstellar molecules in the origin of life ?
- What role do these molecules play in the physical evolution of these regions ?





NASA Ames PAH Data Base: Allamandola, Bauschlicher et al.
Pirali et al. 2006, in prep.
Joblin et al., 2002, Mol Phys, 100, 3595

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MOLECULAR COMPLEXITY

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- What is the molecular
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NASA Ames PAH Data B
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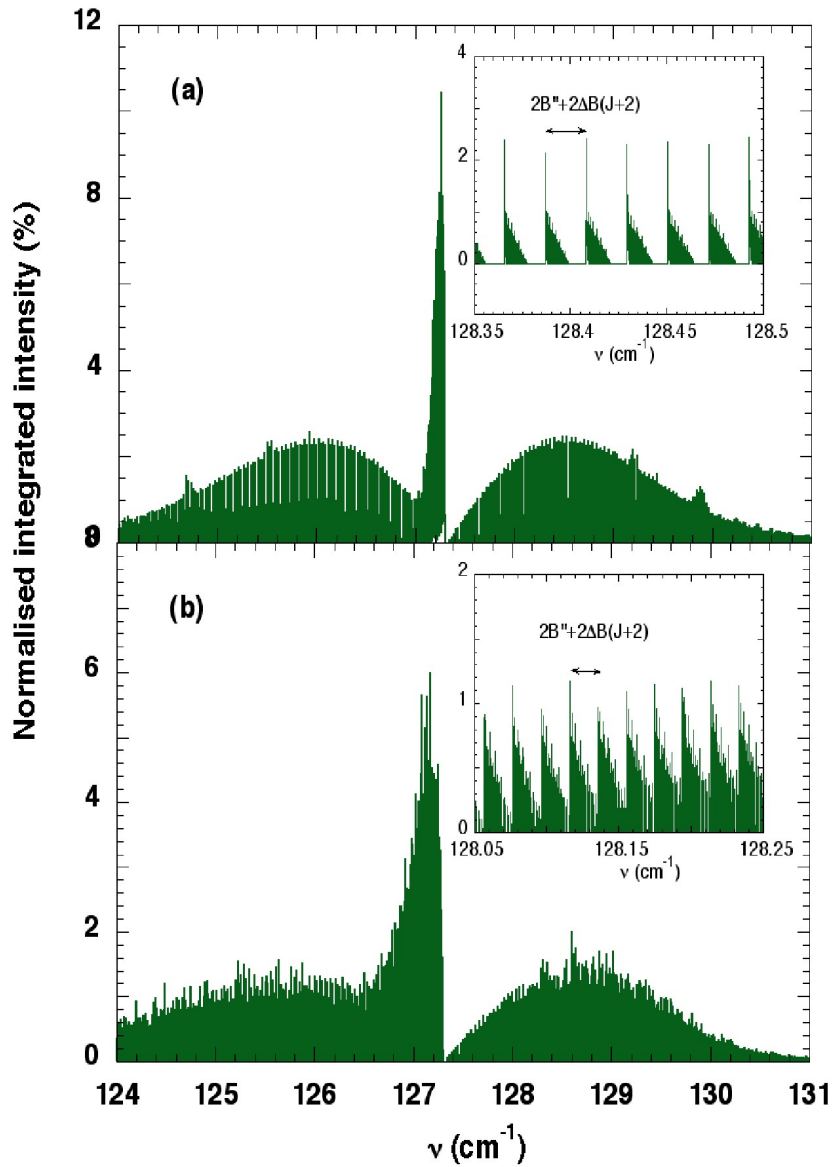

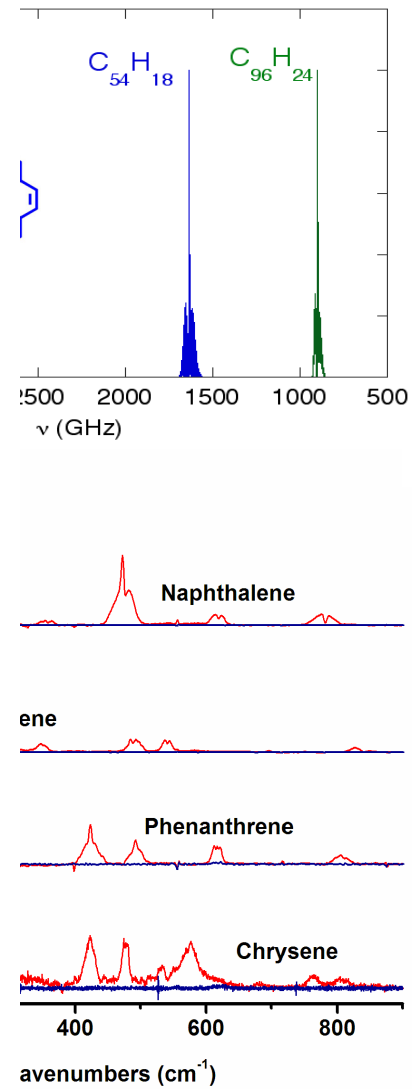

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EVOLUTION OF THE UNIVERSE

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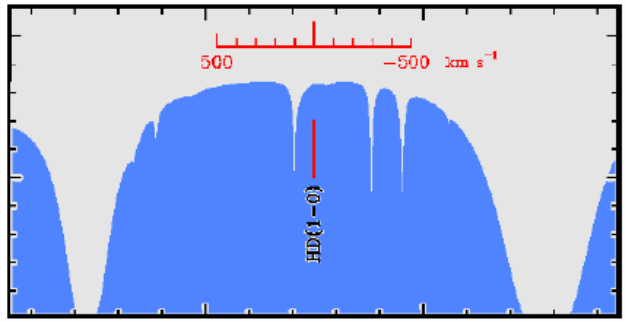
SOFIA will study the deuterium abundance in the galaxy, investigating the evolution of the universe



Atmospheric transmission around the HD line at 40000 feet

Deuterium in the universe is created in the Big Bang and the primordial deuterium abundance provides the best constraints on the mass density of baryons in the universe. However, this Big Bang record is subsequently modified by stellar nuclear burning as material cycles from stars to the interstellar medium and back to stars.

Only the high resolution spectrograph on SOFIA can measure the deuterium abundance throughout our galaxy and answer:

- What is the abundance of deuterium and how does it vary with the local star formation rate in galaxies ?
- What does that tell us about the Big Bang and about the star formation history of galaxies ?

NASA strategic sub-goal 3D.1 and 3D.2

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Lab Astrophysics Data Needs

- Accurate *transition frequencies* and *energy levels*, particularly for high rotational and ro-vibrational states (even H_2O, SO_2, CH_3, etc.)
- Band-strength (or dipole matrix element) data, particularly for radicals, to derive abundances
- Collisional excitation rates
- Knowledge of probabilities of other excitation methods (UV/IR photon absorption)
- Molecular formation/destruction routes
- Data bases which are easily accessible to the community

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What Molecules ?

- You can observe a lot by watching

Yogi Berra

What Molecules ?

- You can observe a lot by watching

  Yogi Berra

- You see what you see because that is what you went looking for

What Molecules ?

- You can observe a lot by watching

  Yogi Berra

- You see what you see because that is what you went looking for
- But what if you went looking for something else

  &

- What if you put on your new glasses ?

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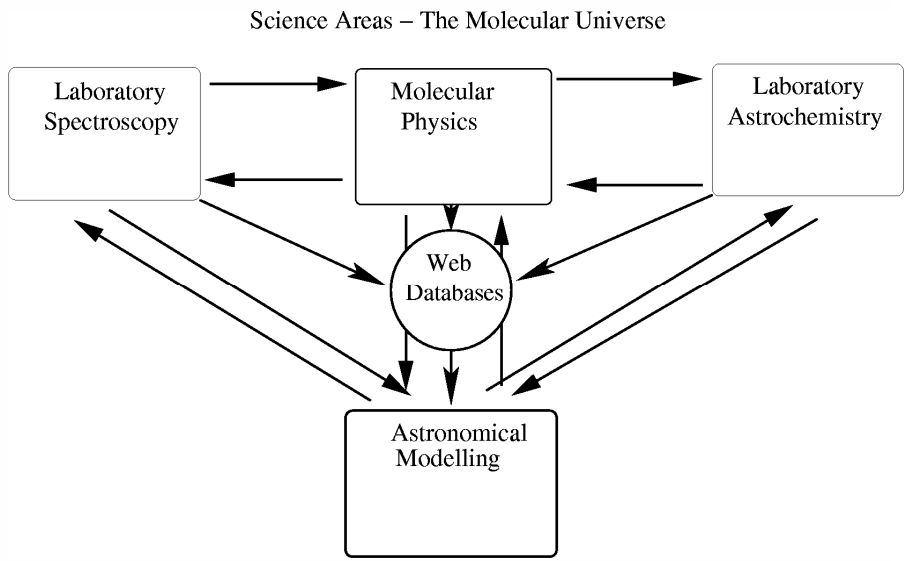
Supporting Laboratory and Theoretical Data

- Challenge
- Multidisciplinary program
  - Molecular physics
  - Laboratory astrochemistry
  - Laboratory spectroscopy
  - Astronomical modeling
  - Data bases
- Solid science but not at the forefront of these disciplines
- Support has to come from NASA



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THE EUROPEAN SCENE

Molecular Universe Network

- Consortium of 21 institutes in 9 European countries in molecular astrophysics
- Coordinator: Xander Tielens;
  co-coordinator: Marie-Lise Dubernet
- EU: Funded as a Marie Curie Research and Training Network through FP6
- Preparation for HIFI (and ALMA)

Teams

SOFIA Stratospheric Observatory for Infrared Astronomy

- Kapteyn Institute
- University of Basel
- University of Bordeaux
- University of Cologne
- University of Durham
- University of Goeteborg
- University of Goettingen
- Grenoble Observatory
- Leiden Observatory
- University of Lille
- CSIC-IEM-DAMIR
- Paris Observatory
- University of Nijmegen
- CNRS-LPPM-University of Orsay
- IAS-University of Orsay
- University of Oxford
- University of Perugia
- University of Rennes
- University of Toulouse
- University of Manchester
- University of Warsow

Table B.1: THE TEAMS AND THEIR EXPERTISES

Team	Molecular Physics	Astrochemistry	Astronomical modeling	Laboratory spectroscopy	Data bases & web interfaces
RuG			X		
Unibas	X			X	
Bordeaux	X	X			X
Cologne				X	X
Durham	X		X		
UGOT		X			
G□ttingen		X			
U.J.F.	X		X		X
Leiden		X	X		
LILLE				X	
Madrid	X		X		X
Meudon	X		X		X
KUN	X			X	
CNRS				X	
UPS			X		
UOXF.DN	X	X			
Perugia		X			
UR1	X	X			
Toulouse III		X			X
UMIST			X		X
Warsaw	X				

Training

- 444 person months
- 9 graduate students (Early Stage Researcher/ESR)
- 5 (joint) postdocs (Experienced Researchers/ER)
- Secondment
- Network meetings and workshops
- Summerschool

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Research

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Interwoven Science Projects

- Molecular complexity in space
  - Water in the universe
  - Carbon chemistry
  - Deuterium chemistry
- Chemistry in regions of star formation
  - Ionization along the star formation trail
  - Nitrogen chemistry as tracer of protostellar condensations
  - Molecular tracers of shocks

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WATER IN THE UNIVERSE

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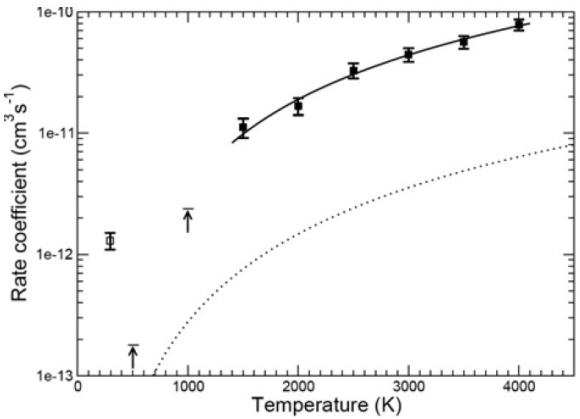
- A coordinated study of the physics and chemistry of H_2O in astrophysical environments
  - Spectroscopy of high excitation levels
  - Potential energy surfaces
  - Theoretical ro-vibrational excitation cross sections
  - Experimental excitation cross sections
  - Astrochemistry of H_2O
  - Radiative transfer of H_2O

vibrational relaxation rates



- Some accomplishments
  - Computation of 9D H_2O-H_2 potential energy surface (Grenoble)
  - Classical vibrational relaxation rates (Grenoble)
  - Quantum state-to-state rotational excitation rates (Meudon)
    - Rotational excitation rates differ by ~20% (ortho H_2) to factor 2 (para H_2)
    - Vibrational rates differ by large factor
  - Radiative transfer models (Groningen)

Faure et al., 2005, JCP, 123
Dubernet et al., in prep.

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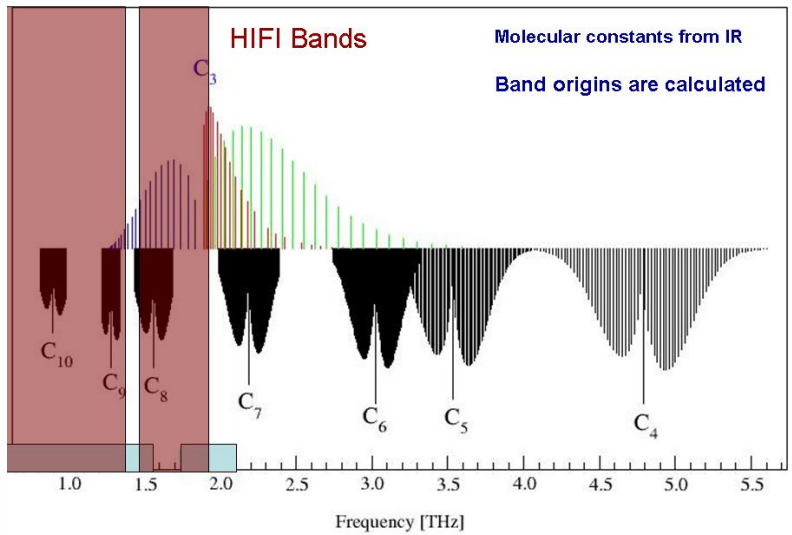
CARBON CHEMISTRY

- A coordinated study of the physics and chemistry of hydrocarbons in astrophysical environments
  - Experimental studies of reaction rate coefficients of hydrocarbons
  - Spectroscopy of PAHs and carbon chains
  - Excitation models for PAHs and carbon chains
  - Astrochemistry of PAHs and carbon chains
- Some accomplishments
  - Experimental study of C and C_2 with C_2H_2 (Perugian, Rennes)
  - Experimental study of photodissociation of small carbon chains (Toulouse)
  - Spectroscopy of carbon chains (Cologne)

Lowest Bending Modes of Linear Carbon Clusters



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Data Bases and Web-Interfaces

- Spectroscopy
  - JPL: http://spec.jpl.nasa.gov/ftp/pub/catalog/catdir.html
  - Cologne: http://www.ph1.unikoeln.de/vorhersagen/
  - Harvard: http://www.cfa.harvard.edu/HITRAN
  - NASA Ames Research Center: http://web99.arc.nasa.gov/~astrochm/pahdata/index.html
- Molecular physics
  - Meudon: http://amdpo.obspm.fr/basecol/
  - Goddard: http://data.giss.nasa.gov/mcrates/
- Astrochemistry
  - UMIST: http://www.udfa.net/
  - Ohio State: http://www.physics.ohio-state.edu/ eric/research.html
  - SWRI: http://amop.space.swri.edu
- Web-interface
  - Toulouse: http://www.cesr.fr/~walters/web_cassis/

Data bases and Web Interfaces

- Tasks
  - Validate data
  - Simulation tools
    - Astrophysical models
    - spectroscopic data bases
    - Synthetic spectra
  - Web interfaces for data bases
- Some accomplishments
  - New version of the UMIST astrochemistry data base

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Summary

SOFIA Stratospheric Observatory for Infrared Astronomy

- NASA missions need
  - Fundamental data
  - Laboratory/theory
- Consortia
  - Interdisciplinary: Physics, Chemistry, Astronomy
  - Concerted efforts involving 5-10 partners
- Challenges
  - NASA is only source of funding for space research
  - Make attractive to young researchers
  - Data bases are the key for the community

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