Beyond Spitzer

The Next Generation of Coherent Detector Systems for Far Infrared Astronomy

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NASA Astrophysics Objectives

- **Structure and Evolution of the Universe**
  - Discover what powered the Big Bang and the nature of the mysterious dark energy
  - Learn what happens to space, time, and matter at the edge of a black hole
  - Understand the structure and the cycles of matter and energy in the evolving Universe
    - Production of chemical elements? Tracing energy and magnetic fields that distribute elements?
    - Extreme astrophysical environments?

- **Origins Objectives**
  - To understand how today's universe of galaxies, stars, and planets came to be
    - How did the cosmic web of matter organize into the first stars and galaxies?
    - Different galactic ecosystems and which can lead to planets and living organisms?
  - To learn how stars and planetary systems form and evolve
    - How do gas and dust become stars and planets?
    - Planetary systems around other stars, their architectures and evolution?
  - To explore the diversity of other worlds and search for those that might harbor life
    - What are the properties of planets orbiting other stars?
    - Terrestrial planets: Abundance? Properties? Habitable?
    - Is there life on planets outside the solar system?

High Spectral Resolution Astrophysics

- **What causes and controls star formation?**
  - Little evidence on how/why molecular clouds collapse
  - Few ways to observe early phases of star formation
    - Optically thick in IR and visible (only see envelop)
    - Often very cold <10K in cold core
    - Most molecules depleted onto grains
  - Little evidence for competing theories
    - Does gravity and turbulence cause collapse?
    - Does magnetic fields allow/prevent collapse?
- **How do planets form in the debris disk?**
  - How do terrestrial planets form?
  - Formation rates and planet types?
  - Distribution of Water and Organic Molecules?
  - Solar system architectures?
  - What remains of the debris disk, how representative of the initial conditions?

High Spectral Resolution Astrophysics

- **The local ISM and implications to other galaxies**
  - What causes molecular clouds to form and dissipate?
  - How diffuse is the diffuse ISM?
  - What is the ISM distribution and phase distribution in the Milk Way?
  - What governs the transport and distribution of molecules and dust in the ISM?
  - What are the carriers diffuse interstellar bands?
  - What are the carriers of the 3 micron PAH bands?
  - Isotopic fractionation and potential depletion in cold clouds?
    - Is Deuterium depleted in molecules and dust?
  - Interaction of stars with the ISM?
  - Chemistry and chemical evolution?
- **All of these topics can be effectively studied by spectroscopy of atomic and molecular lines in the far Infrared.**

Underlying Physics

- **Long Wavelength Spectroscopy: black (gray) body with atomic and molecular features on top**
- **Spontaneous Line Emission**

$$A_{m\leftarrow n} = \frac{64\pi^4 \upsilon_{mn}^3}{3hc^3} \left| \langle m|\mu|n\rangle \right|^2$$

- **Line widths (1/A) <10^{-3} km/s in the Far-IR**
  - **2 Debye at 100μm is A=~10^{-4} sec**
- **Most dense molecular cloud <10^8/cm^2 Collision rate is <1/sec**
  - **Pressure broadening is negligible (<10^{-4} km/s)**
- **In Far IR observed line shape and shift is entirely Doppler**
  - **Line width gives a temperature (300K is a few km/s)**
  - **Line shape probes turbulence**
  - **Relative Velocity (Red Shift)**

Exploiting Line Shapes

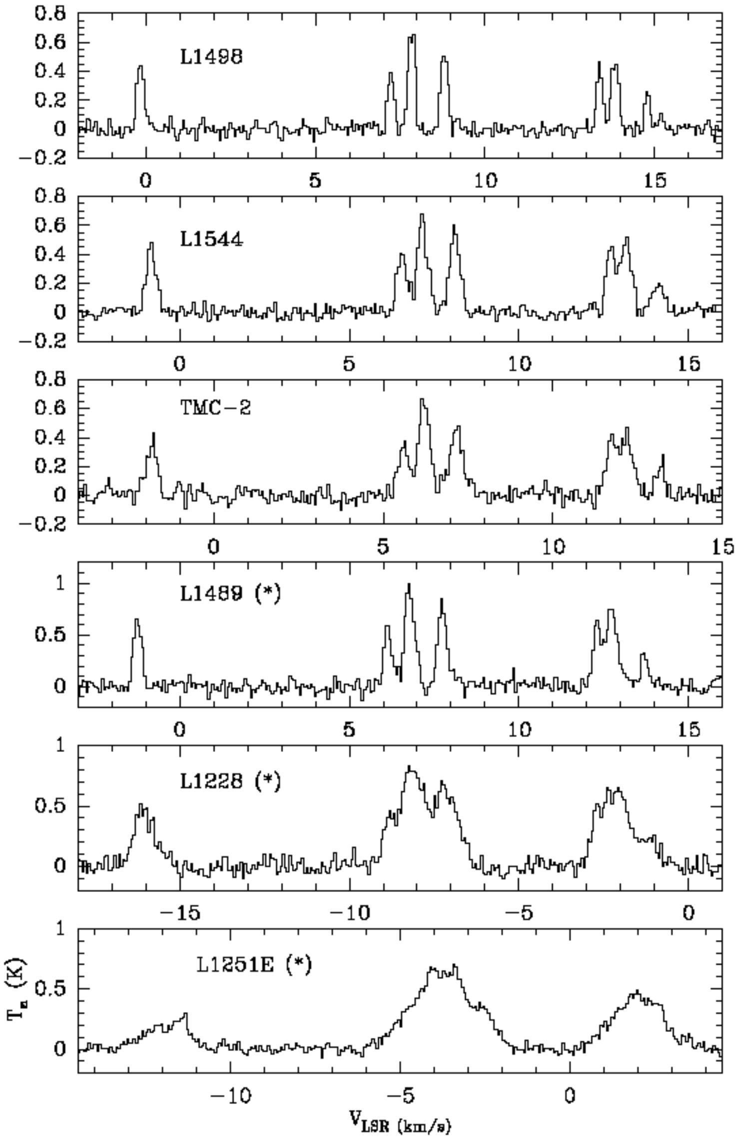
- Exploiting a line shape requires a spectrometer
  - Minimum of 3 spectral resolution elements across the line (10-20 is optimal)
    - Trade-off between sensitivity and information
- In Far Infrared four choices of spectrometers
  - Disperssive Spectrometer (grating/prism or equivalent)
    - R=~10^3 Limited by grating size (R=length/λ)
  - Fabry-Perot Spectrometer
    - R=~10^4 Limited by Finesse of cavity
  - Fourier Transform Spectrometer
    - R=~10^5 Limited by length of moving arm
  - Heterodyne Spectrometer
    - R determined by LO spectral purity and backend spectrometer ~10^8 in Far IR
- For R>10^5 in the Far-IR coherent spectroscopy is the only practical choice.
- For R>10^3 system considerations make coherent worth considering

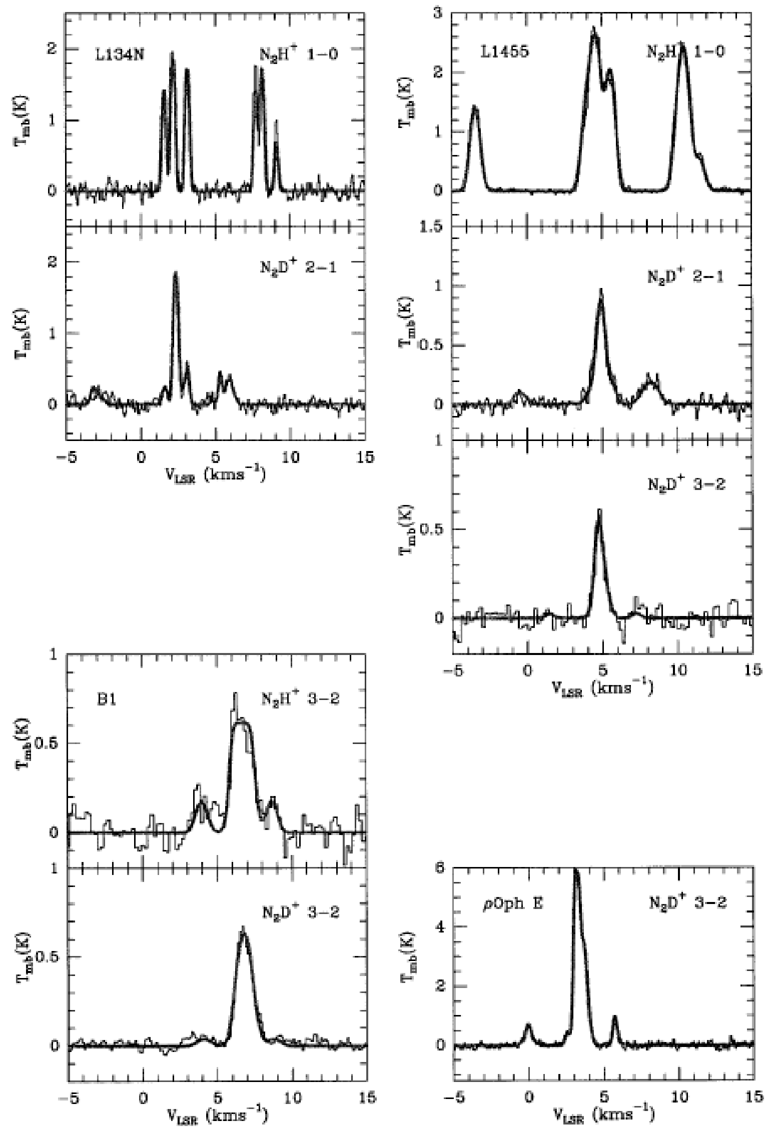
Advantages and Disadvantages

- **Advantages to coherent systems**
  - Cooling detectors below 4K is not critical
  - Warm apertures and optics may be employed
  - Earth orbit (and high data rates) may be used
  - Detectors are insensitive ionizing radiation
  - IF data may be duplicated with no loss
    - Interferogram may be repeated
    - Infinite number of baselines are possible
    - Interferometer baseline is not limited by diffraction
  - Stray light less critical

- **Disadvantages**
  - Limited by quantum noise
  - Difficult to build large arrays
  - Complex system with multiple components
  - Limited Spectral Bandwidth (photometry difficult or impossible)
  - Standing waves everywhere

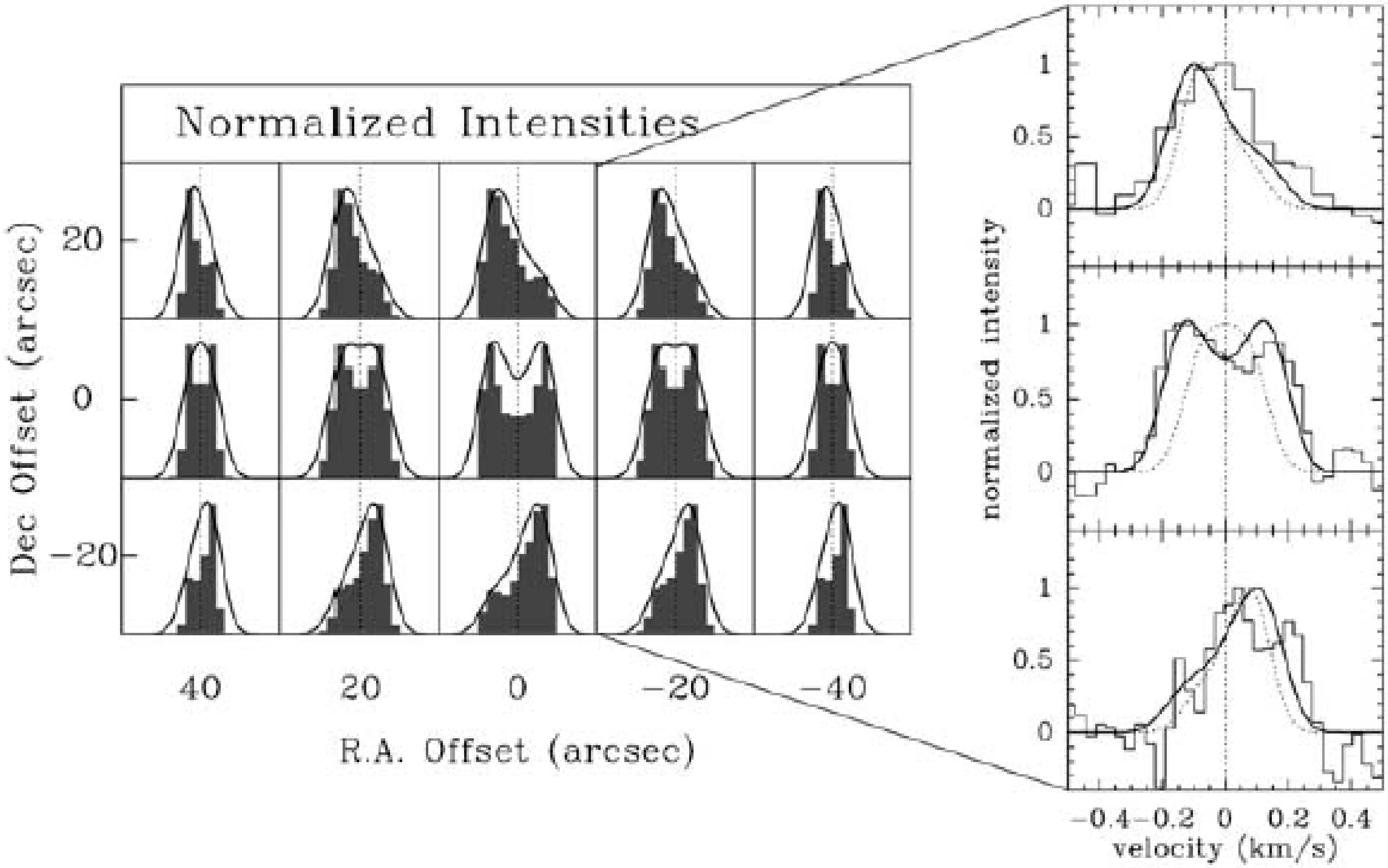
Star Formation Line Widths





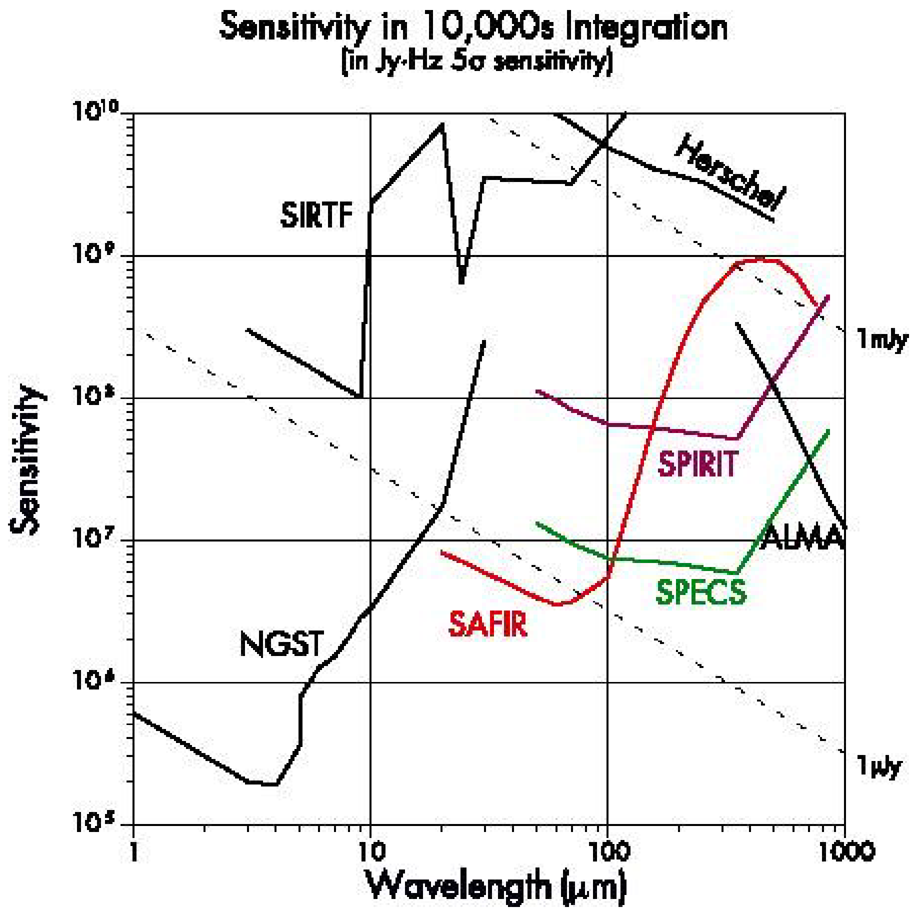
Left N_2H^+ lines in a variety of cores showing progressively more turbulence form Caselli et al. 2002
Right N_2H^+ and D_2H^+ in a variety of cores from Gerin et al. 2001.

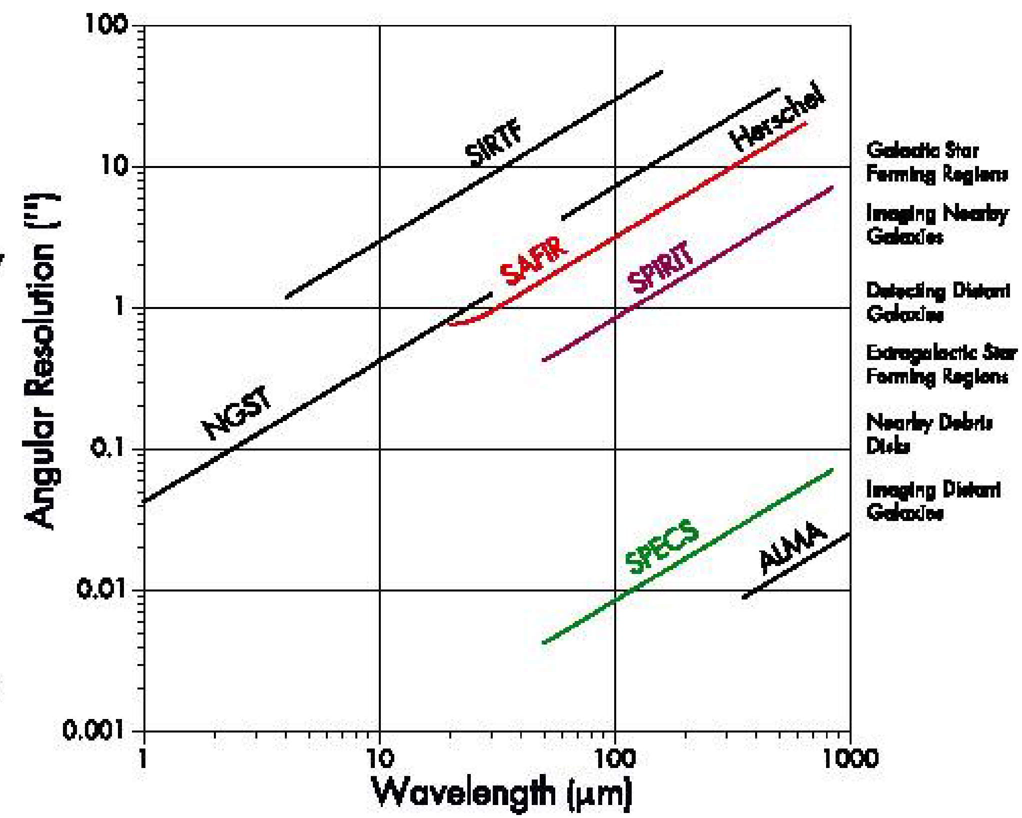
Source Structure = Maps



Model of optically thin line (left) in disk velocity field histogram is kinematic solid line includes 10K thermal broadening. Inset is observation of L1544 N_2H^+ J=1-0 from Caselli 2003

Existing and being Studied





SAFIR is planning to have high spectral resolution
SPIRT will not have high spectral resolution
SPECS would like R~10^5

What Needed & Missing

- High spatial resolution (<1”) with high spectral resolution $R \sim 10^7$
  - Star formation details
  - Limited mapping speed at high angular resolution
  - Requires interferometer multiple apertures
- Rapid line mapping ability $R \sim 10^4 - 10^7$
  - ISM details
  - Interaction of ISM with stars
  - Requires spatial array single aperture
- At higher spatial resolution high spectral resolution becomes more important in studying galaxies.
- Progression of missions to fill gaps under discussion
  - SPICA and SAFIR are on road maps and under study
  - Many proposed missions could fill the longer range gaps
  - Available technology & resources will dictate choices

Existing Far IR Mixer Technology

- **SIS mixer technology (well proven, well understood)**
  - ~3x Quantum limit to 700 GHz
  - 5-10x quantum limit to 1.3 THz
  - Good technical prospects to 1.5 THz
  - Widely used on ground
  - Will never achieve quantum limit above superconductor band gap
- **Hot Electron Bolometer technology (Limited understanding)**
  - 10-20x quantum limit to 5 THz
  - Being used in SOFIA, HERSCHEL and several ground instruments
  - Ultimate sensitivity is an open question (is sensitivity wasted in heat sink?)
- **Other Detectors early in development**
  - Kinetic Inductance
  - Inter-Sub semiconductors
- **IF technology adequate (~100uW per mixer)**
  - lower dissipation would help arrays

Existing LO Technology

- **Harmonic generation (works to ~2 THz)**
  - Power will be limited above 1 THz
  - Noise grows with number of harmonics and will eventually become a problem
  - Currently expensive and complex at high frequencies
- **Gas Lasers**
  - Large DC power required
  - Single frequencies
- **Emerging technologies**
  - Laser mixing
    - Poor conversion efficiency to date
  - Quantum cascade lasers (promising to about 1.5 THz)
    - No control scheme (yet)
    - DC Power and heat load still quite high

Systems

- Systems expertise is needed in two areas
  - Spatial arrays of receivers
    - Several ground based systems have been employed
  - Phase array systems
    - CARMA, SMA, ALMA will do basic development
    - Higher frequency issues need to be addressed
- Receiver components must be simplified
  - Increased functional integration (MMIC style implementation)
  - Automated test and assembly
  - Reduced unit cost
- Support equipment requiring development
  - Coolers
  - Lower power back end spectrometers
  - deployable apertures
  - down link bandwidth

Conclusions

- **The future is usually determined by what can be implemented**
  - **Coherent receivers to make high resolution spectral and spatial maps can be implemented on short time scales with largely existing technology**
  - **The science return is enormous and complementary to other operational missions**
- **A large single dish (SAFIR or an Origins concept is needed in the short term)**
  - **Good reasons to optimize the mission for high resolution spectroscopy or photometry**
- **An interferometer with very high spectral resolution is required for star and planet formation details**
  - **Molecular depletion requires this instrument to look at hydrogen molecules**
  - **Habitability questions requires the instrument to study water**