The Hidden Universe revealed at submm wavelengths

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Plan of lectures

I. The Cold Universe. Basic observational properties of the ISM and galaxies at FIR-mm wavelengths. Overview of reasons why submm observations are a necessary contribution to the understanding of the evolutionary history of galaxies and clusters. History of FIR-mm astronomy.

II. Dust grains and thermal radiation. IR-mm wavelength spectral energy distributions of starburst galaxies. Calculation of dust masses & SFRs. K-corrections. Arguments to support expectation for luminous submm galaxies in the high-redshift universe.

III. Submm telescope & instruments. Confusion limits, biases & survey design. Results from submm galaxy surveys. Evolutionary history of submm population. Multiwavelength follow-up (including molecular gas content) of high-redshift submm population.

The history of structure formation in the Universe

- where and when did the first galaxies form?
- how does the star formation density evolve in galaxies?
- do most high-z stars form in large galaxies, or in small ones?
- are the star formation history and gas consumption in galaxies connected?
- how is the formation of supermassive black-holes related to the formation of galaxies?
- what is the spatial and redshift distribution of high-redshift clusters?
- what is the influence of dark matter on the formation of structure?
Formation and evolution of structure at sub-mm wavelengths
The Hidden Universe revealed at submillimetre wavelengths

“submillimetre” wavelength range ~ 50 µm - 1 cm

- 5 µm - 50 µm          mid-IR
- 50 µm - 200 µm         FIR
- 200 µm - 1 mm          submm
- 1 mm - 10 mm           mm
- 1 cm - 100 cm          radio

Primary emission mechanisms

- Thermal (dust & CMB)
- Bremstrahlung (ionized gas)
- Rotational line-transitions (molecular gas)
- Synchrotron (relativistic electrons)

Secondary emission mechanisms

- Inverse Compton Scattering
FIR - radio wavelength observations probe the
cold Universe
- $T_{\text{CMB}} \sim 3 - 30$ K ($0 < z < 10$)
- $T_{\text{cirrus}} \sim 15 - 25$ K (also neutral HI gas)
- $T_{\text{dust}} \sim 15 - 60$ K (also molecular gas)

young Universe
- formation on many scales starts in cold, dense environments (optically-invisible)

massive Universe
- neutral atomic (HI) & molecular gas (CO) comprise 80% of mass in ISM in late-type galaxies in the local universe or almost all the mass in high-redshift galaxies (depends on SFR & duration of starburst during major formation epoch)

An oversimplification - but generally structure starts in cold and dense environments (i.e. sub-mm bright) and evolves (grows) to become hot, diffuse (low density) & bright in the optical-IR regime.
Black-body intensity (Planck function) & Wien Displacement Law

\[ B_\nu(T) = \frac{2\hbar}{c^2} \nu^3 \frac{e^{\hbar \nu / (kT)} - 1}{e^{\hbar \nu / (kT)} - 1}, \]

\[ B_\lambda(T) = \frac{2\hbar c^2}{\lambda^5} \frac{1}{e^{h\nu / (\lambda kT)} - 1}, \]

\[ \frac{d}{d\nu} \left\{ \frac{2\pi \nu^3 \hbar}{c^2 [e^{\hbar \nu / (kT)} - 1]} \right\} = 0 \]

\[ \nu(B_\nu) = \frac{kT}{\hbar} \left( 2.821 \right) = (5.879 \times 10^{10} \text{ K}^{-1} \text{ Hz})T. \]

\[ \lambda(B_\nu) = \frac{hc}{4.965kT} = \frac{2.898 \times 10^{-3} \text{ K m}}{T}. \]
Blackbody emission curves for different solar system bodies

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>Titan</td>
</tr>
<tr>
<td>200</td>
<td>Mars</td>
</tr>
<tr>
<td>300</td>
<td>Earth</td>
</tr>
<tr>
<td>600</td>
<td>Venus</td>
</tr>
<tr>
<td>6000</td>
<td>Sun</td>
</tr>
</tbody>
</table>
CMB fluctuations

$T_{\text{CMB}} \sim 2.7 \text{ K}$

$\delta T/T \sim 10^{-5}$

CMB blackbody peaks at $\sim 1 \text{ mm}$
Seeds of large scale structure formation

now WMAP (l < 800) +


temperature power-spectrum (Netterfield et al. 2002)
Higher-resolution CMB experiments to complement COBE, WMAP & balloon-borne instruments (e.g. BOOMERANG)

**Cosmic Background Imager (CBI)**
- Located at the ALMA cite in Chajantor, Chile. These 13 (x 0.9m) antennae operate at 26-36 GHz.

**Arcminute Cosmology Bolometer Array Receiver (ACBAR)**
- On VIPER telescope at South Pole
  16 receivers @ 150,220,280 GHz

**Degree Angular Scale Interferometer (DASI)**
- A sister project to the CBI, located at the South Pole. With baselines of 1-6m, CBI is sensitive to scales of 3-20 arcmin.

Beam-sizes (FWHM) of order 1-5 arcmins for these experiments
Cool dust (T = 15 – 25K) in our Galaxy

100 µm cirrus emission < 1 MJy/sr (500mJy/beam, 150” FWHM)

< 2 MJy/sr

“Holes” in the Galactic cirrus (HI + dust) emission allow a view to the high-z Universe with minimal Galactic foreground contamination

e.g. Lockman Hole, ELAIS N1 & N2 with $I(100\mu m) < 0.3\,\text{MJy/sr}$
Cirrus emission in the Galaxy with IRAS at 100 microns

for images & data see http://astron.berkeley.edu/davis/dust/
HI and dust correlation (cirrus)
cold, atomic, neutral HI (and possible cold dust) in the Galactic ISM & intergalactic medium
The Leo Ring

optical

cold atomic, neutral HI (blue contours)
Interacting galaxies

HI (blue)
Optical (green)

NGC 4038/9 VLA HI (blue) and CfIO Optical (green), from Hibbard, van der Hulst & Barnes 1999
notice the difference in resolution between IR-mid IR images and the FIR images.

even in nearby galaxies it is difficult to resolve individual regions of star formation in the FIR with existing instruments on satellites (e.g. Spitzer)
Spiral Galaxy M51 ("Whirlpool Galaxy")

Visible

Spitzer Space Telescope • IRAC

Ssc2004-19a

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)
Visible Mid-IR
dust
optically-obscured star formation
Visible + Infrared

Sombrero Galaxy/Messier 104

Spitzer Space Telescope • IRAC

Visible: Hubble Space Telescope/Hubble Heritage Team

NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team

ssc2005-11a
Dust in Supernova - but how much mass?
Kepler’s Supernova Remnant • SN 1604

NASA, ESA / JPL-Caltech / R. Sankrit & W. Blair [Johns Hopkins University]
Observing optically-obscured (hidden) star-formation with submm observations

sites of SF

optical HST

sub-mm 450μm
M82 (NGC3034)
D=3 Mpc
small edge-on irregular (spiral?) galaxy

brightest extragalactic IR source in sky

Subaru optical image

Halpha → dust lanes

IRAS 100 microns
diffraction spikes of secondary mirror
M82 (NGC3034)  D=3 Mpc

edge-on dusty, molecular torus
obscuring central star-forming clusters

40 Jy integrated flux at 450µm

Subaru optical image

UKT14 450µm Hughes et al. 1994

sub-mm map
HST vs. SCUBA maps of Hubble Deep Field
SCUBA survey of the Hubble Deep Field
Hughes et al. 1998, Nature, 394, 241
Which is the counterpart to the brightest submm source in HDF?

but not the z~1 passive elliptical, so perhaps lensed by the elliptical.
**SCUBA survey of the Hubble Deep Field**

optical vs. submm view of star-formation history (circa 1998)

To discriminate between alternative evolutionary histories, we need statistically-large samples of sub-mm galaxies & accurate redshifts

Hughes et al. 1998, Nature, 394, 241
Evolution of luminosity density due to star formation
(i.e. star formation history of the Universe)

adopted from Rafael Guzman (Lecture II)
γ-ray to radio extragalactic background emission

\[ \log(\lambda) \ (\mu m) \]

\[ y_L (nW \cdot m^{-2} \cdot sr^{-1}) \]

\[ \log \nu \ (Hz) \]
Extragalactic background radiation: energy output at FIR-mm wavelengths is comparable in strength to the optical background, yet < 1 sq. degree (0.002%) of the submm sky has been mapped, and < 50% of submm/mm background has been resolved.
First FIR extragalactic observations

review: Dust in Galaxies, Stein & Soifer 1983
Annual Review of Astronomy & Astrophysics Vol 21

“... we have attempted to be upto date as of June 1982.”

• Galactic centre - bright 100um source Hoffman & Frederick (1969)
  dust within HII/region & molecular cloud complexes
  responsible for FIR emission (Hoffman et al. 1971; Harper & Low 1971)

• M82 (dusty, irregular galaxy) : Harper & Low (1973)
  brightest extragalactic object in IRAS catalogue at 60 & 100um (> 1983)

  L(FIR) ~ 2 \times 10^{10} \text{ Lsun}, comparable to optical luminosity
  Half the total luminosity of M51 emerges at reradiated thermal emission
  from dust at FIR wavelengths !!!!
Development of extragalactic FIR-mm astronomy

FAR-INFRARED OBSERVATIONS OF GALACTIC NUCLEI

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ABSTRACT

M82 (NGC 3034) and NGC 253 have been detected at wavelengths between 27 and 125 µ. Their respective 3–3000 µ luminosities are $5 \times 10^{10} L_\odot$ and $3 \times 10^{10} L_\odot$. A 2σ upper limit of $760 \times 10^{-26}$ W m$^{-2}$Hz$^{-1}$ has been established for the 110-µ flux from NGC 1068.

Subject headings: galactic nuclei — infrared sources

I. INTRODUCTION

The infrared continua of many galactic nuclei rise sharply to a peak beyond 20 µ, and the infrared luminosity is, in many cases, greater than the radio and optical luminosity (Low and Kleinmann 1968). Only in the case of our own galactic nucleus has it been possible to make accurate infrared observations at wavelengths near the maximum in the flux distribution. Repeated attempts to confirm the 50–300 µ detection of NGC 1068 (Low and Aumann 1970) have failed. Here we report a new upper limit on the far-infrared flux of NGC 1068 and the first measurements at these wavelengths of NGC 3034 (M82) and NGC 253. Our most recent observations of Sgr A are also reviewed.

II. OBSERVATIONS

Development of extragalactic FIR-mm astronomy

1973

No. 2, 1973
FAR-INFRARED OBSERVATIONS
L91

1990

Figure 3. Radio to X-ray continuum energy distribution of M82. The open squares indicate new 800- and 1100-μm data presented in this paper. The solid squares are various data collected by KWM in addition to recent data at 1300 μm (Thronson et al. 1989) and at 450 μm (Smith et al. 1990). The dashed-dotted line shows the free-free emission continuum, the dotted lines show the 47 and 155 K thermal dust emission, whilst the solid line represents the combined 3-mm-10-μm thermal dust emission from M82.

Figure 1.—Spectral power distributions of galactic nuclei. All data points between 10^{12} and 10^{13} Hz are from this paper. The solid lines drawn through these points are proportional to 60° Planck functions (the spectral distribution assumed when converting broad-band flux ratios to flux densities). Other data were taken from Rieke and Low (1972b), Becklin et al. (1973), Harper et al. (1972), Rieke et al. (1973), Wynn-Williams et al. (1972), Fomalont (1968), and Keilman and Penney-Teth (1971). The λ < 20 μm points for M82 may be underestimated by as much as a factor of 1.5–2 because of beam-size effects. The constant C is 2.5 for W3 (G133.7 + 1.2) and zero for all other sources.
Summary - Lecture I

• Significant mass in the baryonic universe is associated with the cold & dark atomic (HI), molecular (H₂) & metallic (dust) interstellar medium (ISM) that radiates at sub-mm wavelengths

• Atomic and molecular gas (raw material for star formation), and dust grains (for cooling of the gas) are the key ingredients to build galaxies

• The earliest stages of star formation are invisible at UV-IR wavelengths

• 50% of the extragalactic background radiates at FIR-mm wavelengths & only a tiny fraction of submm sky has been surveyed with sufficient sensitivity to resolve the individual galaxies that contribute

Need to significantly increase the scale (area) and sensitivities of surveys undertaken at submm wavelengths. The next lecture will describe the feasibility of suitable surveys with the next generation of ground-based, airborne, sub-orbital, and satellite observatories and instruments.