Submillimeter Astronomy

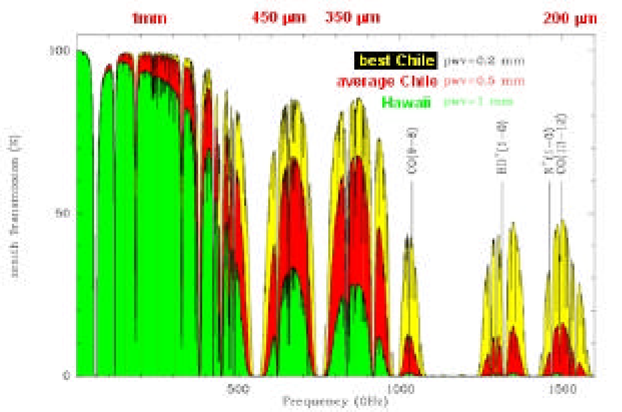
The law derived by Max Planck at the turn of the 20th century says that *any* body with a temperature emits its maximum amount of radiation at a certain wavelength, λ, or frequency, ν, that is uniquely determined by the body's temperature. (frequency is inversely proportional to wavelength, i.e., $\nu = c/\lambda$, where c is the speed of light for electromagnetic radiation). At longer wavelengths the body emits less and at shorter wavelengths much less than at that wavelength. Planck's is the fundamental law that describes all thermal phenomena in the Universe, phenomena whose emission is caused by their temperature. For example, a human body (310 Kelvin) emits maximally at 9.3 micrometers (µm), i.e. at infrared wavelengths.

Our sun, at a temperature of 5800 K emits maximally at a wavelength of 0.50 µm, where our Earth's atmosphere is transparent (an important factor for life's evolution). However, the atmosphere is not at all or little transparent at almost all other wavelengths, except for radio waves longward of 1 cm (*see figure to the upper right*) This means in particular that the interstellar medium, the "material between the stars" from which stars form, is difficult to observe from the ground. Cold dark molecular clouds such as B68 (*see lower right figure*), having a temperature of 10 K only (10 degrees above absolute zero), emit maximally at 550 micrometers. This is in the middle of the so-called *submillimeter* range, which one may define as the wavelength region between 1000 and 200 µm (300 – 1500 Gigahertz, GHz).

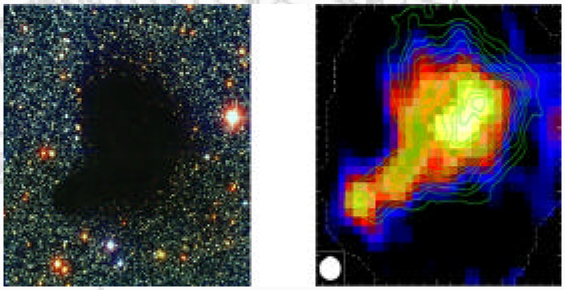
Submillimeter astronomy is the astronomy of the cold and the warm. Many molecules (and the carbon atom) emit spectral lines in this range. The frequency of a line, ν, is given by $\Delta E/h$, where ΔE is the difference between the upper energy level, from which the line is emitted, to the lower level and h is the Planck's constant. Different energy states correspond to different (quantized) rotational states and a line is emitted with every change in rotational state. Higher states need higher energies (= temperatures) to be excited. Measuring lines of different excitation states for a given molecule and comparing their intensities allows in fact a determination of the gas temperature, while a line's intensity is a measure of the concentration of molecules along the line of sight.

Molecular line emission occurs at discrete frequencies, which are measured to high accuracy in specialized laboratories (like the Cologne Laboratory for Molecular Spectroscopy).

Dust is the other important ingredient of the interstellar medium. In contrast to molecules, its emission varies smoothly with frequency, with the intensity growing toward shorter wavelengths (Planck's law!). Dust is mostly a nuisance at optical wavelengths, where it appears in absorption, blocking the light of farther-away sources (*see image of B68 above*). In contrast, at (sub)millimeter wavelengths dust appears in *emission* and its intensity can be used to infer the density of the material averaged over the line of sight and its mass.



Transmission of the Earth's atmosphere between 0 and 1500 GHz (wavelengths smaller than 200 µm) for a 5000 meter high site. The area in green maps out conditions (1 mm precipitable water vapor, PVW) typically found on Mauna Kea, Hawaii (4000m altitude). The red areas denote average conditions prevailing on the 5100 m high APEX site Chajnantor. Extremely good conditions are marked by the yellow area. Note that the difference in observing conditions between these scenarios is dramatic as high atmospheric opacity (= low transmission) not only increases the emission of the atmosphere, effectively adding receiver "noise", but also attenuates the incoming radiation. Both effects work exponentially! For ground-based sites the atmosphere is completely opaque between 1700 and 10000 GHz.



The left hand panel shows an optical picture of the dark globule B 68 absorbing background starlight. The right hand panel gives a false colour representation of the dust emission from B68 at a wavelength of 1.2 mm. This map was made with the SEST. Strong spectral line emission from a number of molecules is observed towards the same area from which dust emission arises.

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Comets to Cosmology – the Submillimeter Universe and the Tools to Observe It

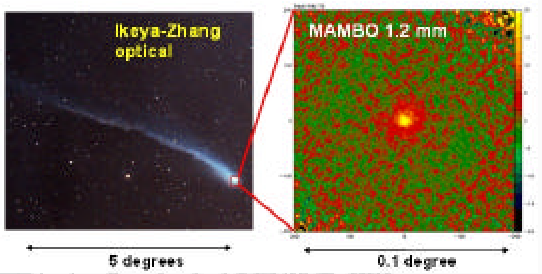
The detectors needed to detect continuum emission are quite different from those used for spectral-line detection ("spectroscopy"). The latter employ the *heterodyne principle* which means that the submillimeter radiation is down converted to lower (radio) frequencies, which are technically easier to manage. In this process the phases of the waves are preserved, which allows spectroscopy. This means that the light can be split into fine frequency intervals so that narrow spectral lines can be resolved. Continuum detectors work quite differently. The most sensitive ones, "bolometers", employ the fact that the incoming radiation causes a minute temperature change in the detector, resulting in a measurable change in its electric resistance. Such bolometers are extremely sensitive because of their very wide bandwidth, usually covering a whole atmospheric window. State of the art heterodyne receivers are built at, both, the MPIfR and OSO. In addition, the MPIfR has one of the world's leading bolometer groups.

While most of the scientific interest in submillimeter astronomy is indeed in the observation of interstellar gas, *anything* emitting radiation in this band can be a worthwhile target. Results pertaining to the physics of the interstellar medium in our own and external galaxies are amply described in the accompanying flyers. To complement, in the following we present two examples of MPIfR (sub)millimeter solar system astronomy and cosmology.

These results were obtained with the instruments of the Institute for Radioastronomy at Millimeter Wavelengths (IRAM) – the 30m telescope on Pico Veleta, Spain, and the Plateau de Bure Interferometer in the French Alps. APEX is extending the line of these preeminent mm-wavelength telescopes to shorter wavelengths.

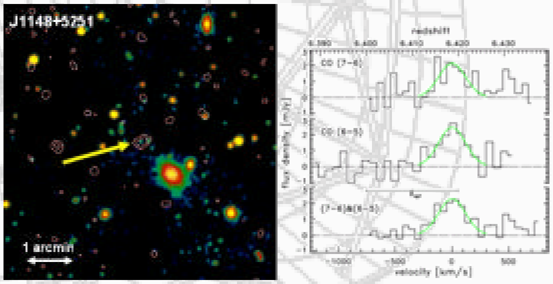
The MPIfR Bolometer Groups has a long-standing commitment to building 1.2mm wavelength bolometer arrays for the 30m telescope, thus gaining the expertise to build the Large APEX Bolometer Camera (LABOCA; see separate flyer).

From the nearest…



The left hand side shows an optical image of comet Ikeya-Zhang, while the right hand side shows 1.2 mm continuum emission from the innermost region of the coma and the nucleus in false color. Such observations provide an estimate of the nuclear diameter and the dust production rate. Note the difference in scales.

…to the farthest



Left: Overlaid on a false-color near-infrared image from the Sloan Digital Sky Survey the contours show emission at 1.2 mm emitted from dust in the quasar J1148+525. This is, at a redshift of 6.418, the farthest known quasar in the universe. The 1.2 mm observations were made with the MAMBO array at the IRAM 30m telescope. Right: High excitation emission lines from carbon monoxide redshifted from submillimeter wavelength ranges into the mm-wave bands accessible with the IRAM Interferometer. The observed radiation left J1148+5251 at a time when the universe had just 6% of its present age! APEX is observing these and similar lines in the local universe, placing these results into context.

Credit for Figures:
B68/Optical image: European Southern Observatory
Ikeya-Zhang/Optical image: Gerald Rhemann and NASA Jet Propulsion Laboratory
J1148+5251/Optical image: Sloan Digital Sky Survey
IRAM is a collaboration of the Max-Planck-Society, the French Centre National de la Recherche Scientifique and the Spanish Observatorio Astronómico Nacional