

Advances across a broad range of technologies are rapidly transforming the submillimeter spectral region—long considered the “gap” in the electromagnetic spectrum—from a region inhabited by specialists into one that is fulfilling its long anticipated potential. After considering the physics underlying interactions in the submillimeter region, the author describes its rapidly expanding presence in fundamental laboratory studies as well as the major astronomical and atmospheric science facilities that are being built to explore it.

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Science and Technology in the Submillimeter Region

It has long been known that the region between about 3 mm (100 GHz) and 100 μm (3.3 THz) is rich in scientific and technological opportunities.^{1,2} It has also long been known that reaping them poses significant technological challenges. Some of the opportunities have been realized, with major efforts in laboratory spectroscopy, astronomy and atmospheric remote sensing firmly established. Others, in areas such as imaging, communications and the spectroscopy of solids, remain in a period of extended adolescence. In the context of particular approaches or scientific communities, the region in question has been referred to by many names: millimeter, nearmillimeter, submillimeter, far infrared and terahertz. For the purposes of this article I will use the term submillimeter (SMM), although I will seek to address in general terms the properties and opportunities this region encompasses.

The basic physics of the SMM

The interaction of electromagnetic radiation with matter determines the observed character of each spectral region. Because of the energy scales of atoms and molecules, radiation in the optical region interacts with electronic levels, infrared radiation interacts with molecular vibrations, SMM interacts with molecular rotations and the radio interacts with nuclear multipole phenomena. Additionally, especially in liquids and solids (which in the SMM do not have energy levels that are as sharply defined as those in other regions), there are interactions which are more conveniently described by classical ideas such as conductivity, dielectric constant or loss tangent.

Because rotational motion ordinarily requires a gas phase system, there is a special relationship between the SMM and rotational gas phase interactions. Additionally, the interaction between submillimeter radiation and molecular rotation is very strong and the Doppler limited linewidths are very narrow. This makes the SMM very favorable for many applications. In general these rotational interactions start in the conventional microwave region but have strengths that grow as the cube of the frequency until they reach a maximum

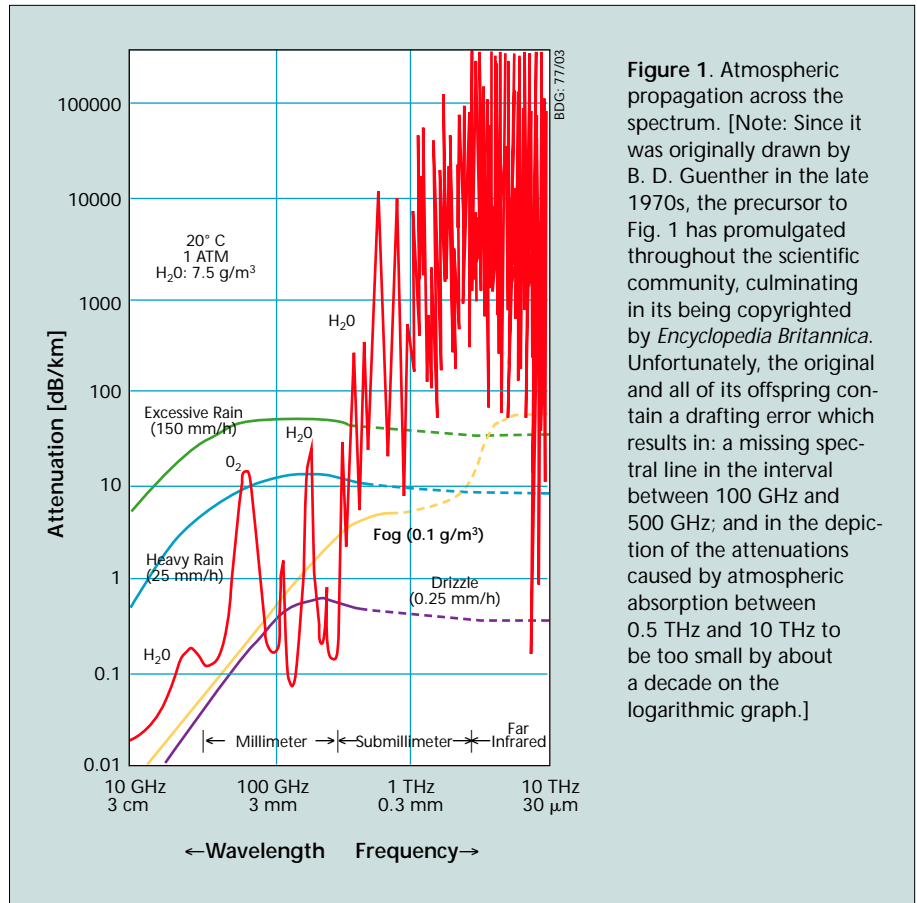


Figure 1. Atmospheric propagation across the spectrum. [Note: Since it was originally drawn by B. D. Guenther in the late 1970s, the precursor to Fig. 1 has promulgated throughout the scientific community, culminating in its being copyrighted by *Encyclopedia Britannica*. Unfortunately, the original and all of its offspring contain a drafting error which results in: a missing spectral line in the interval between 100 GHz and 500 GHz; and in the depiction of the attenuations caused by atmospheric absorption between 0.5 THz and 10 THz to be too small by about a decade on the logarithmic graph.]

somewhere between a few hundred GHz and a few THz, after which point they drop exponentially.³

The atmosphere: an overview example

These strong interactions also cause significant and complex attenuation in Earth's atmosphere. Because of the central role played by atmospheric attenuation in many SMM applications and also because propagation can serve as a useful illustration of much of the physics of this spectral region, let us begin by considering Fig. 1. In Fig. 1 are plotted the absorption due to atmospheric gases (in the SMM, primarily oxygen and water) and the classical scattering from water and fog droplets. The scattering attenuation is approximately constant, starting at short wavelengths, until the wavelength of the radiation is approximately droplet size (in this model, essentially constant for rain and more complex for the assumed varying droplet size distribution of fog). This general relation between the

size scale of the scattering media and wavelength makes the SMM attractive both for imaging with useful resolution over modest distances (~1 km) and for proximate imaging through dust, rain, woven dielectric materials and so forth.

Although as expected molecular attenuation peaks in the SMM, the variation is much greater than casual inspection of Fig. 1 might imply. For example, attenuation changes from less than 1 dB/km (a transmission of about 80%) near 100 GHz, to losses of greater than 100,000 dB/km (a transmission of $10^{-10,000}$) near peaks of water lines around 1 THz.

While this attenuation can compromise applications that require good atmospheric propagation, the same rotational interactions also provide the strong absorptions and emissions that make this spectral region favorable for molecular science. Since the frequencies of the peak interactions are a function of molecular size and the vast majority of molecules are larger than water, the peak

absorptions of the heavier molecules are shifted to lower frequency relative to those of water.

What makes the SMM unique?

The characteristics that make the submillimeter region so special are:

Matter/radiation interaction

Classical electromagnetic theory simply scales with wavelength and frequency. Our everyday experience, however, puts us into contact with regions of the electromagnetic spectrum with which specific properties are associated: for X-rays, penetration and resolution; in the visible, imaging and sight; in the infrared, thermal imaging and vibrational spectroscopy; in the microwave and radio, communications and radar. This enormous variety comes about largely because of the multiplicity of ways in which radiation interacts with matter *and* the temperature of the world we live in. In the following section I will explore these interactions in the SMM, a region of which the public and most members of the scientific and technological communities do not possess an intuitive picture.

Separation of the wave function

It is remarkable that so much of matter can be understood by separating its descriptions into those associated with electronic, vibrational, rotational and nuclear degrees of freedom. At a quantum mechanical level, this description results from the separation of the energy scale of each from its neighbors by one or more orders of magnitude. This makes possible the separation of the Hamiltonian into pieces, which often interact only weakly with each other. There are classical pictures as well. In a molecule, for example, the energetic electrons travel around the nuclei in their orbits at high speeds in comparison to the vibrational motion of the nuclei. Thus, the nuclei only “see” the average position of the electrons and are little affected by the details of the electronic motion.

Thermal populations

The properties of the world we live in are not determined only by the energy levels available but also by which ones

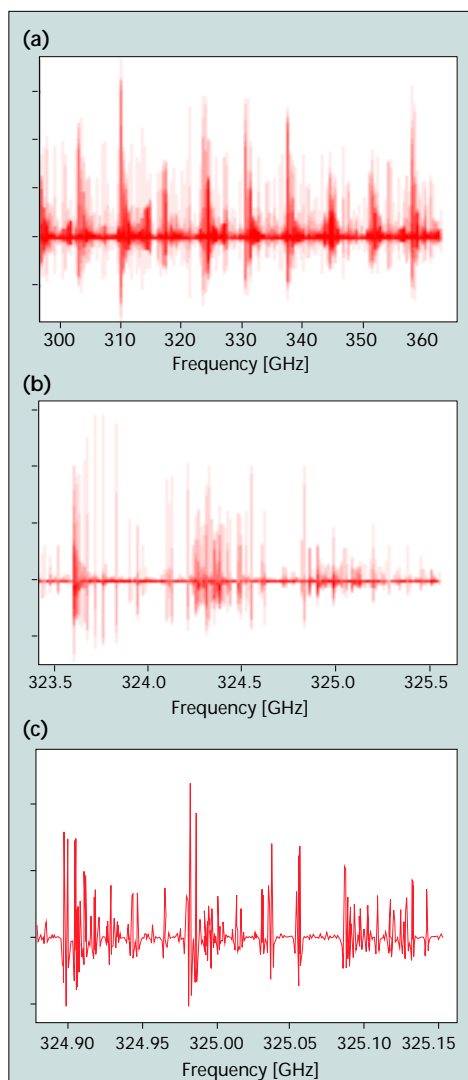


Figure 2. Spectrum of cyano oxirane (C_3NOH_3) between 298 and 363 GHz (a), between 323.5 and 325.5 GHz (b) and between 324.9 and 325.15 GHz (c).

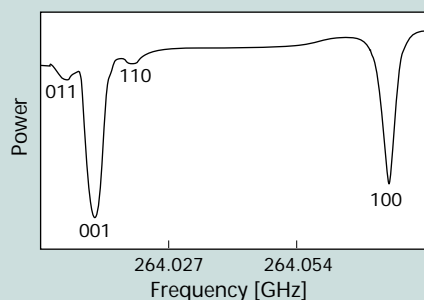


Figure 3. The $J = 2-3$ rotational transitions of excited vibrational states in the plasma of the HCN discharge laser.

are occupied or energetically accessible. For systems at or near thermal equilibrium, the ratio of the populations of two states is determined by the Boltzmann distribution $N_u/N_l = \exp(-h\nu/kT)$. We live on a planet with a sun the photons of which are energetic enough to interact with the electronic degrees of freedom. But on Earth kT ($T=300$ K) $= 200$ $cm^{-1} = 1/40$ eV $= 6000$ GHz is much greater than $h\nu_{rot}$. As a result, our optical technology operates in a world where systems at or near thermal equilibrium are almost entirely in their electronic ground states and optical excitation energies far exceed thermal dissipative energy scales. In the SMM at ambient temperature, however, $h\nu \sim kT$. The character of both the technology and science in this region is profoundly affected as a result.

Interactions

Intimately connected to this population distribution is the nature of how matter interacts with itself to move from one energy level to another. In gases the exchange mechanism is typically the exchange that occurs during a collision between translational energy (which is of the order kT) and internal degrees of freedom; in condensed matter the energy exchange is more collective. Irrespective of the agent of energy exchange, however, when the levels are separated by $< kT$ and connected by a transition moment (e.g., a dipole-dipole interaction in the gas phase), the probability of energy transfer is high. Likewise, when the separation is $> kT$, exchange is slow. This energy relationship has significant impact on the selective excitation and relaxation of levels in lasers and other quantum devices and the dividing line occurs at $\nu \sim kT/h$.

Typical SMM spectrum

While atmospheric transmission is an important example of gas phase interactions, the widely spaced energy levels of water and oxygen are atypical, as is the high atmospheric pressure. Figure 2 shows as a series of blow-ups the spectrum of oxirane between 298 and 363 GHz obtained with a Fast Scan Submillimeter Spectroscopy Technique (FASSST) system.⁴ This system substitutes fast scanning and digitization for the phase-lock frequency reference

typical of SMM spectroscopy. In this example the scan time for the complete region was approximately 2 seconds, or a rate of approximately 10^5 resolution elements/second. The information content of this figure serves to illustrate the power of the physics that underlies matter-radiation interactions in this spectral region. To plot the entire spectrum of the upper graph on the scale of the still-compressed lower plot would require a graph approximately 50 meters long. Additionally, in the vertical dimension all of the apparent “noise” peaks on the baseline are, in fact, weak spectral lines.

Why is the SMM unique technologically?

The factors that make the submillimeter region special from a technological point of view are:

The physics of the gap

The SMM is often referred to as the “gap” in the electromagnetic spectrum because of the historical difficulty associated with developing a technology, especially a robust source technology, capable of operating in this region. There are, of course, well known fundamental reasons for the difficulty. The gap can be explained by the fact that size limitations on classical microwave sources occur below $\nu \sim kT/h$, where quantum systems begin to become practical. Classical sources typically require a size scale small enough so that, as the electrons traverse an interaction region, the phase of the field does not reverse and reabsorb the energy that was just transferred from the electron to the field. This sets a size scale of approximately λ for the interaction structures, typically significantly less for conventional e-beam voltages and velocities and much less for solid state devices. While modern fabrication technologies can easily produce high quality structures on this subwavelength scale, as frequency is increased, the resistivity of metals increases, the cross sectional areas available to the electron currents decrease, heat dissipation becomes more difficult and so forth. In contrast to these classical devices, lasers and other quantum mechanical devices can operate in large high order mode structures that couple together the collective contributions of

While the thermal power emitted in this spectral region is relatively small, the associated noise is even smaller, typically by many orders of magnitude.

many atomic or molecular systems. However, radiation sources are easiest to build at energies that are large compared to kT , so that the collisional and other dissipation processes discussed above do not rapidly drive population inversions toward equilibrium.

Source demonstrations

These challenges have produced a multitude of approaches to the source problem.^{1,2} Examples include: broadband sources that use spatial interference for frequency selection (Fourier transform with thermal, discharge or time domain radiation sources); fundamental oscillators (classical electron beam, free electron lasers and solid state); harmonic generation from lower frequency sources; and mixing from optical sources.

The spectral width of sources

While it is not the purpose of this article to review the characteristics and relative merits of these approaches, it is perhaps useful to note that most SMM applications can be separated into those with linewidths which are very broad or perhaps continua (solids, liquids and high pressure gases) with $Q < 100$, and those with gases which are in general very narrow, with $Q > 10^5$. Appropriate technologies for these applications can often be similarly divided, although there are many cases in which spectrally pure sources are desirable even for the investigation of phenomena without sharp resonances.

Source brightness

For many applications, an appropriate figure of merit is the integral of the source brightness [W/Hz] over the spectral width of the phenomena to be stud-

ied. To provide a numerical reference point, 1 mW of power within a 1 MHz Doppler limited line corresponds to a brightness temperature of approximately 10^{14} K. Alternatively, this brightness over a terahertz bandwidth requires a total average power of 1000 W. As another measure, a discharge tube of effective temperature 2500 K emits 10^{-11} W into a 1 MHz bandwidth at 300 GHz.

Coherent and incoherent detectors

Because of the difficulty of generating power in this region, considerable attention has been paid to the integration into SMM systems of sensitive coherent or incoherent detectors. Coherent detectors require either a local oscillator (frequency domain) or timing pulse (time domain). The sensor elements for coherent and incoherent detection are usually the same: semiconductor diodes, photoconductors, bolometers and so forth.

Noise considerations

It is fortuitous that because the quantum limit to noise is much smaller in the SMM than at shorter wavelengths, in this spectral region it is possible to build sensitive receivers of both classes. It is also fortuitous that the noise that is radiated—even from harsh environments such as discharges and high temperature systems—is insignificant in the overall noise performance of most SMM systems. This is because while the thermal power emitted in this spectral region is relatively small, the associated noise is even smaller, typically by many orders of magnitude. Consider a typical ^4He incoherent detector with an NEP of 10^{-12} W/Hz^{-1/2} and a cooled filter with a 1 THz cutoff. The noise from a blackbody at 300 K over this region is approximately 10^{-14} W/Hz^{1/2}. Even for somewhat higher temperatures and/or higher frequency cut-offs, this is much lower than the detector noise. Stated in terms of source power, the environmental noise is about 11 orders of magnitude below that of a 1 mW cw source.

Applications: a few examples

A symbiotic confluence of advances and major projects is producing a new era for science and technology in the SMM and making possible exciting visions of the

future. In this section I will discuss a cross section of examples.

Since it can be argued that the most important and unique characteristic of the SMM is its strong interaction with the rotational degrees of freedom of molecules, it is not surprising that most of the applications and projects are based on this interaction. Examples include fundamental studies of molecules, remote sensing in the atmosphere and the exploration of the interstellar medium and the universe. In addition, there has been a longstanding interest in the use of a wide range of SMM technologies for applications that do not require high spectral resolution. These include radar and imaging, the study of semiconductors and other solids and biomedical applications. While many of these are of interest to the SMM community and a number of contributions have been made,¹ I will not discuss them here since they were recently described in a feature article published in OPN.⁵

Basic science: gas phase molecules

Spectroscopy

The source and detector considerations discussed above have led to an active and successful submillimeter spectroscopy based on coherent, tunable, CW sources and broadband thermal incoherent detectors.^{4, 6-8} The specificity and sensitivity shown in the SMM spectrum of Fig. 2 are the basis for both laboratory and field investigations. In the laboratory the fundamental application is spectroscopy itself: an extensive community studies line positions, intensities and linewidths in a variety of molecular species. Some of this work is carried out for its own intrinsic interest; some is driven by the need for laboratory data for the interpretation of the astronomical and atmospheric applications described below. There has also been considerable use of these capabilities for the investigation of physical and chemical processes under non-ambient conditions. Because the same physics that makes the generation of radiation in the SMM difficult also makes even harsh environments quiet, this spectral region has been used advantageously for the study of equilib-

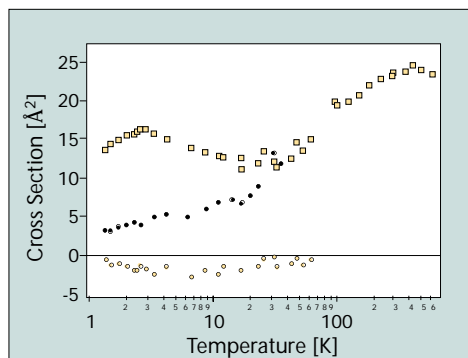


Figure 4. Divergence of elastic (*upper*) and inelastic (*lower*) cross sections at low temperature for H₂S-He collisions. The points below zero are the pressure shift cross sections.

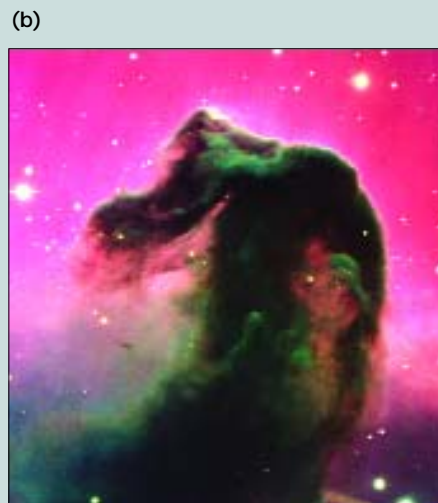
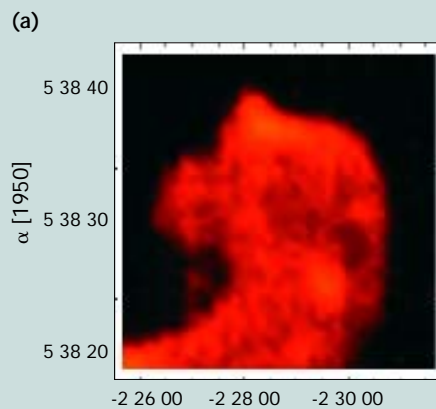


Figure 5. (a) The Horsehead Nebula, as observed in the J=3-2 emission from CO at 345 GHz by the Cal Tech Submillimeter Observatory (CSO) and (b) in an optical image.

rium systems over 1-2000 K^{9,10} and active laser plasmas^{11,12} to name but two of many examples.² Figure 3 shows the J = 2-3 rotational transitions of HCN in four different excited vibrational states as observed in the discharge of a HCN far infrared laser. This spectral region is so quiet that even broadband helium temperature detectors do not observe *any* additional noise in these experiments.

Energy transfer

As noted above, $h\nu_{\text{SMM}} \sim h\nu_{\text{rot}} \sim kT$ in the SMM. This makes it a fertile region for the study of molecular energy transfer. Of particular interest in our laboratory has been the study of gas phase collisions at temperatures of only a few degrees K. This required the development of collisional cooling, a method for studying gas phase systems in quasi-equilibrium, at temperatures far below their freezing points.^{13,14} In these collisions, the basic physics changes and many phenomena that are “classical” at 300 K reveal their underlying quantum nature. Figure 4, for example, shows the divergence of the elastic and inelastic cross sections at low temperature for the H₂S-He collision system. This divergence is caused by collisions that change the phase of the molecular wave function without causing a change in state. In the elastic cross section, a thermally averaged resonance can also be observed near 3 K. This type of resonance is a feature of low orbital angular momentum collisions at low temperatures in which resonant excitations can cause the formation of quasi-bound states.

Astrophysics: the physical conditions

By far the largest SMM community has grown up around astrophysics. To date, more than 100 different chemical species have been identified from their emission lines. Regions that contain molecules are typically at temperatures of a few Kelvin to a few hundred Kelvin and which are well suited to emission in the SMM. The strong molecular rotation-radiation coupling adds to the sensitivity of the technique. In addition to research in the field of astrochemistry,¹⁵ probes based on molecular emissions in the SMM (especially of CO, which has been shown to have a nearly constant abundance ratio



Image courtesy of NRAO/AUI and ESO

Figure 6. Artist's rendition of part of the ALMA array of 64 12-m antennas.

with the astrophysically abundant and significant hydrogen) have become powerful probes of a wide range of astrophysical processes. Many of these applications are greatly facilitated by the ability of longer wavelength SMM radiation to penetrate the dust clouds that hide many of the most interesting astrophysical processes, especially star and planet formation.

The Horsehead Nebula in Orion is a particularly interesting example. In the well known optical image [Fig. 5 (b)] the dust which forms the horse's head by optical extinction stands out as a dark feature against the optical emission in the background. In the SMM image, quite the opposite occurs: here the CO *within the dust*, the attenuation of which produces the optical image, propagates freely through the dust and reveals the structures within the dust cloud.

Telescopes and technology

This field has grown to such an extent as to preclude even a brief description of the major ground, airborne and satellite facilities that are operating today around the world. However, descriptions of two of the most recent, ALMA and Herschel, can give some idea of the work that is being carried out. ALMA, for Atacama Large Millimeter Array, is an array of 64 12-m dishes (see Fig. 6) being built at

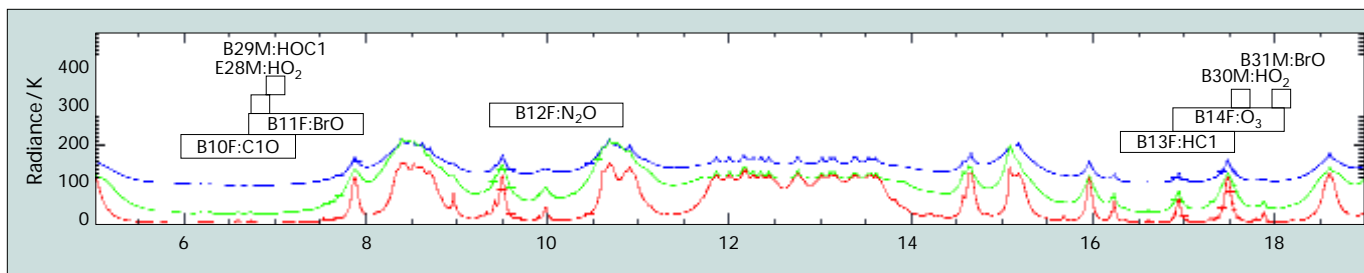
16,400 ft in the Atacama desert in Chile to avoid as much atmospheric attenuation caused by water vapor as possible. Scientists working at ALMA will study cosmology, star and planetary formation, stellar evolution, molecular clouds and astrochemistry in the ~ 30 GHz to ~ 400 GHz region. The interferometer baselines can be configured from approximately 150 m to 10 km, which translates into better resolution in the SMM than the Hubble Space Telescope provides in the visible. At its full 10 km extent, its baseline is approximately 1,000 times that used to produce Fig. 5. This additional resolution will provide far more detail on the dynamics of, for example, star- and planet-forming regions. It will also remove the spatial averages over regions of significantly varying physical properties and make possible a much better understanding of astrochemistry.

Although Mauna Kea (the location of CSO) and Atacama (the future home of ALMA) are arguably the best sites in the world for SMM observations, their performance at high frequency is severely compromised by the atmosphere. In parallel the European Space Agency, with

significant NASA participation, plans in 2007 to launch Herschel, a 3.5-m telescope with an instrument temperature maintained by superfluid helium. Because it operates above Earth's atmosphere, it can observe from 60 to 670 μm with three instruments: a heterodyne high resolution spectrometer (HIFI) with bands of 480-1250 GHz, plus 1410-1910 GHz; a photoconductive array camera and spectrometer (PACS) for 210-60 μm ; and a spectral and photometric imaging receiver (SPIRE) for bands centered on 250 μm , 350 μm and 500 μm . The system will be used to focus on how galaxies formed in the early universe, as well as on star and planet formation. With its multitude of phase-locked oscillators, frequency multiplier chains, cooled mixers, bolometers and photodetectors, (all of which have to survive launch with high reliability) the system testifies to the maturity of this technology in the SMM.

Atmospheric science

Another important application is the remote sensing of chemical species that contribute to the ozone chemistry of the upper atmosphere.¹⁶ Observations have been made from the ground, from balloons and from spacecraft. Spacecraft offer the advantage of global coverage on a 24-hour basis. In addition, because they



work above the atmosphere, attenuation and noise associated with the lower atmosphere are avoided.

A recent example is the Earth Observing System-Microwave Limb Sounder (EOS-MLS), which is scheduled to be launched as a part of the Aura mission in 2004. Figure 7 shows the portion of the simulated spectrum around 650 GHz for EOS-MLS. This is a limb scanning instrument that samples the radiation along the line which extends from the spacecraft through the tangent point closest to Earth and then to the background of space. Since all altitudes above the tangent point are sampled, somewhat triangular lineshapes result. However, this shape (as well as multiple spectra taken for different tangent heights) can be used to deconvolute the contributions from the various altitudes. It can be seen in Fig. 7 for the strong lines that the antenna temperature saturates near the temperature of the atmosphere for all tangent heights, whereas for weaker transitions, because the sample is optically thin, the antenna temperature is lower. Another interesting feature of this spectrum is that the lines narrow as the tangent height is increased, reflecting the reduced pressure broadening along the limb sounding path.

Imaging

While there have been demonstrations of terrestrial imaging based on a wide variety of SMM technologies, these astronomical and atmospheric instruments are powerful imaging devices that in many ways serve as guideposts for the development of practical terrestrial imaging systems. Some, like the CSO 12 m, produce images by mechanical scanning of the antenna. Others—like PACS and SPIRE of Herschel—have focal plane arrays, while ALMA reconstructs its images interferometrically from detailed

Figure 7. SMM spectrum in the region around 640 GHz to be observed by MLS. The blue trace is for a tangent height with a pressure of 100 mb; the green for a tangent pressure of 30 mb; and the red for a tangent pressure of 10 mb. The frequencies shown in the figure are the offset from the 642.87-GHz local oscillator.

frequency and phase information. MLS is able to construct a three dimensional image with pointing information from its antenna and altitude information obtained from deconvolution of the pressure broadened lineshapes it observes along its limb scanning line of sight.

The future

Even with these successes, there have been orders of magnitude fewer resources and effort devoted to exploiting the SMM than to any of the other regions of the electromagnetic spectrum. The region has gone through several cycles of growing expectations, entry of new investigators and disappointing results. But this was all in the past. The steady progress of SMM technology and laboratory applications has culminated in major astrophysical and atmospheric projects that have pushed the technology to a new level of capability and robustness.

Nanofabrication and the mass markets of wireless communications, collision avoidance radar and so forth are reaching ever higher frequencies and approaching the SMM. These forces, as well as contributions from other technical approaches, promise to provide the critical mass necessary to move many applications out of their extended adolescence and into a maturity and usefulness comparable to those of other regions of the electromagnetic spectrum.

Finally, as technology in the SMM becomes a tool rather than a specialty, it is highly probable that the exposure of

this spectral region to a much broader community will result in new and important applications that are completely unseen by the present community of experts. Let's not forget that the first application for telescope time by Buhl and Snyder in the 1970s to use microwaves to look for molecules in the interstellar medium was rejected because the conventional wisdom of the astronomical experts was that polyatomic molecules did not exist in space.¹⁷

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