NEW INSTRUMENTS, NEW SCIENCE: FUTURE OPPORTUNITIES

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Abstract. The new millimeter and submillimeter wavelength telescopes will provide a detailed view of galaxy formation, the formation of stars and planetary systems, and the chemistry of the envelopes of evolved stars. The keys to the future are larger and more precise telescopes, quantum limited electronics, and superb observatory sites.

1. Overview

Millimeter and submillimeter astronomy has developed rapidly over the past 25 years in large measure because the observing technology developed so rapidly over the same time frame. In the past two decades the noise temperature of the receivers used at the CO(J=1$\rightarrow$0) line has decreased from roughly 1000 times the photon noise limit, $h\nu/k$, to a value only a few times this limit, an improvement of more than two orders of magnitude. The sizes of our telescopes have increased from 11 m to 30 m, an increase in angular resolution of a factor of 3 and an increase in collecting area of a factor of 7. Finally, the application of aperture synthesis interferometry at millimeter and submillimeter wavelengths with interferometer baselines of several hundred meters has increased the angular resolution to the point that now images may be made at a resolution equivalent to that obtained at optical and IR wavelengths.

The progression of increasing technical capabilities has given us scientific insight unexpected with the observing capabilities of previous years. We now know that molecular emission can be studied not only in Galactic molecular clouds but also throughout the disks of nearby galaxies and, indeed, in luminous galaxies at cosmological distances. We know that the molecular chemistry in the expelled envelopes of evolving AGB stars is determined by both the star itself and the nature of the interstellar radiation field in which the star is immersed. We know that dusty protostellar disks are ubiquitous, that their dust emission is sufficiently bright to be detectable at millimeter wavelengths, and that once so identified, the disk kinematics can be revealed by molecular spectroscopic observations of sufficiently high angular resolution. But whereas we are aware of what can be learned at millimeter and submillimeter wavelengths from our existing observing technology, we are also aware that in all the cases mentioned above we are presently observing "tip-of-the-iceberg" phenomena: we see only the most luminous cosmological galaxies, only the nearest AGB stars, only the bright, nearby protostars. We cannot put these observations in the larger astronomical context; we are missing the insight they have the potential to provide owing to the limitations of our observing facilities.

The future millimeter and submillimeter telescopes will allow us to overcome these limitations. They will provide us with sufficient increases in sensitivity and angular resolution and with access to enough of the frequency spectrum that our observations will be comparable or superior to the complementary data we will obtain with the new generation of infrared telescopes. In so doing we will achieve the suite of capabilities necessary for the understanding of the physics of cosmic sources of thermal emission. Much of the future advance at millimeter and submillimeter wavelengths will come from larger, high precision telescopes equipped with quantum-limited receivers and located on very dry high elevation sites.

2. New Instruments

Now in construction, or well along in the planning stage, are two large millimeter-wavelength single dish telescopes, the NRAO Green Bank Telescope (GBT) and the UMass/Mexico Large Millimeter Telescope (LMT) and four millimeter and submillimeter interferometer arrays; the Smithsonian Submillimeter Array (SMA), the international Millimeter Array (MMA) project led by the NRAO, the Japanese Large Millimeter and Submillimeter Array (LMSA), and the European Large Southern Array (LSA). As presently conceived, these instruments have somewhat comparable capabilities blending different emphases on millimeter-wavelength sensitivity, angular resolution, and submillimeter performance. All will play important roles in defining the future of millimeter-wave astronomy as described below.

3. New Science

3.1. THE DISTANT UNIVERSE

The discovery that emission from gaseous CO and CI can be detected in galaxies at redshifts greater than two opens the door for investigations of galaxy evolution in the earliest stages wherein a gravitational accumulation of matter in the early universe (a protogalaxy) evolves from being principally gaseous to becoming principally stars. To follow this evolution one needs to observe the gas in emission so that one can map out its spatial distribution and kinematics with the intention of comparing these images to images of light from the earliest stars as detected by the new 8 meter class optical/IR telescopes. Millimeter/submillimeter observations are the only way to image the gas content of protogalaxies, and this will be done very effectively with the new telescopes.

The large single dishes, the GBT and the LMT, will play an important role in detecting the redshifted CO emission from cosmologically distant galaxies. As an example of their effectiveness, let us consider the redshifted CO(J=3→2) emission from the $z = 2.3$ galaxy IRAS F10214+4724. Scoville et al. (1995) show that the peak flux density of this line observed at 105 GHz is approximately 15 mJy. The expected performance of the GBT at 100 GHz will be less than half that at the longer wavelengths and the site is limiting, but under good weather conditions with a 3 mm HFET amplifier and a spectral resolution of 25 km s^{-1}, the GBT sensitivity should be 5 mJy in one minute of integration (two polarizations). This means that the peak of the F10214 CO(3→2) line will be detected at 3σ in a minute. In an hour of integration we get to 25σ, and in 10 hours, 75σ. This suggests that in a long, 3-10 hour, integration "normal" galaxies with 1/10 the CO luminosity of F10214+4724 are detectable with the GBT, at redshifts greater than one. We can expect similar performance from the LMT; although the aperture is smaller, the site is better and the efficiency will be higher.

The large synthesis arrays will image the distribution and kinematics of this gas. The LSA with its planned 10000 m^2 of collecting area will be particularly effective for imaging redshifted CO at 3 mm wavelength. We can expect the observing times needed to be comparable with those above for the GBT, namely a few minutes for lines as bright as those from F10214 and a few hours for galaxies with 1/10 the molecular mass of this ultraluminous object. We return to this point below.

The images of redshifted CO obtained with the MMA, LMSA, and LSA are important for our understanding of galaxy formation, but searching for forming galaxies with the CO line observations is not an effective approach. Instead, dusty galaxies at all redshifts can be most effectively discovered through observations of their redshifted thermal dust continuum emission.

TABLE 1. Cumulative Number of IR Galaxies

Flux Density (mJy)	Frequency 230 GHz	345 GHz
1.0	1.5×10^7	7.5×10^7
0.1	3.8×10^8	1.6×10^9
0.01	5.0×10^9	1.5×10^{10}

Here the idea is to make use of the "inverted" shape of the Rayleigh-Jeans spectrum which, when redshifted, causes the steep "K-correction" to compensate for the $1/r^2$ distance effect as galaxies are observed at increasing redshift. Detailed calculations (e.g., Blain and Longair 1993) indicate that this compensation is so effective that if a given galaxy is detectable at millimeter/submillimeter wavelengths at $z \approx 0.1$, then that same galaxy will be detectable at $z > 5$; the observed flux density will be essentially unchanged.

How many galaxies are likely to be detectable? The IRAS survey allows us to make such an estimate since we can construct a far-IR luminosity function, refer this to models of stellar formation and stellar evolution, and then carry the calculation out to high redshift (earlier epochs). Such a detailed calculation has been made by Franceschini et al. (1991). Figure 1 shows the number of galaxies per steradian as a function of flux density for various wavelengths between 1300 and 25 microns. Let's just consider two of these wavelengths, 1300 and 800 microns. Integrating over the whole sky, Table 1 gives the number of IR galaxies we expect as a function of flux density.

Over the whole sky there are more than 15 million such galaxies detectable at a level of 1 mJy or greater at 230 GHz and there are more than 75 million detectable at the same level at 345 GHz.

The continuum sensitivity goals for the MMA for a minute of integration at 230 and 345 GHz are 0.1 and 0.2 mJy beam^{-1}, respectively. With this sensitivity, the thermal dust continuum emission from 15 million galaxies is detectable at 230 GHz by the MMA at a signal-to-noise ratio of 10 or greater with one minute of observation each. At 345 GHz, 75 million galaxies are similarly detectable at a signal-to-noise ratio greater than five. The sensitivity of the other planned arrays is likely to be similar. This is a very rich scientific field indeed.

Finally, for the MMA and LMSA, which emphasize good submillimeter capability, a galaxy such as the Milky Way provides very luminous submillimeter and far-IR lines that will be redshifted into the observing bands

Figure 1. Integrated counts of galaxies at the wavelengths (microns) shown. (From Franchesini et al. 1991)

and will provide us with a tool in addition to CO for the study of cosmologically distant galaxies. Table 2 gives the luminosity of important cooling lines from the Milky Way as seen by COBE (Wright et al. 1991). The line flux density S_L in Jy, that we would observe from a galaxy identical to the Milky Way at redshift z from a line of luminosity L is

$$S = S_L\ \Delta v = \frac{0.01(L/10^6\,L_\odot)}{\nu_{\mathrm{rest}}/(1+z)} H_0^2 q_0^4 Q^{-2}$$

where $Q = q_0 z + (q_0 - 1)[(1 + 2q_0 z)^{1/2} - 1]$. For the Milky Way, the lines of greatest observed flux density are the NII and CII lines that will be red-

TABLE 2. Spectral Luminosity of the Milky Way

Species	(GHz)	$L/L_{\odot}$
$CO(1\rightarrow0)$	115	$< 5 \times 10^4$
$CO(2\rightarrow1)$	230	7.9×10^4
$CO(3\rightarrow2)$	345	1.3×10^5
$CO(4\rightarrow3)$	461	1.3×10^5
CI	493	2.0×10^5
$CO(5\rightarrow4)$	577	1.0×10^5
CI	810	3.2×10^5
NII	1460	5.0×10^6
CII	1900	5.0×10^7
OI	2060	6.3×10^5
NII	2460	7.9×10^6

shifted at $z > 1$ to the short submillimeter bands. The MMA and LMSA will emphasize these submillimeter lines in the study of cosmological galaxies. The LSA will employ its greatest collecting area at millimeter wavelengths to study the fainter, low order CO lines in these same galaxies. Taken together, the instruments provide astronomers with the needed tools for study of the early universe.

3.2. THE GALAXY NEARBY

In the Milky Way itself, the great sensitivity of all the new instruments will permit studies to be made of the ensemble of AGB stars throughout the disk of the galaxy. The important question here has to do with chemical variations as a function of galactocentric radius, which will tell us of the pace of star formation in the galaxy over the past ten billion years. Additionally, the sub-arcsecond angular resolution of the MMA, LMSA, and LSA will reveal for us the physics of the mass loss process, what physical and chemical processes occur in the expelled stellar envelope, how dust forms and where it forms in the outflow, and how much mass is ejected into the galaxy that will serve as fuel for the next generation of star formation. These studies are presently impossible because the sub-arcsecond resolution is not available at any wavelength at which the stellar envelopes are transparent and because the spectral sensitivity of existing instruments is inadequate. The new arrays will pioneer this research field.

The sub-arcsecond angular resolution of the new arrays will also give us the first clear image of the way in which planets form around young solar-like stars. A resolution of $0.1''$ at the distance of active sites of star formation near the Sun such as in the Taurus, Ophiuchius, or Coalsack molecular clouds correspond to a linear extent of less than 10 A.U. On this scale we will explore the radial density distribution of protoplanetary disks and seek to confirm observationally the speculation that forming planets create azimuthal gaps in the circumstellar disk. We can uniquely study planets in formation because we observe at wavelengths long enough that the disk is transparent but short enough that the thermal emission from the disk is bright. The chemistry of protoplanetary disks, perhaps even the pre-biotic chemistry, will be a rich and previously unexplorable field of research because the proper angular resolution at the proper wavelength was lacking. The new instruments will change all this.

Finally, and closest to home, the new imaging instruments will allow us to see features on objects in the solar system with a clarity that exceeds that of the HST or the new 8 m class optical telescopes operating at their diffraction limit. The resulting spectroscopic images will reveal for us the winds on Mars, Venus, and the giant planets, the chemical composition of comets, and the out-gassing of volcanoes on Io.

The new millimeter and submillimeter wavelength telescopes will make the meeting "Fifty Years of Millimeter Wave Spectroscopy" in 2020 very different scientifically from the meeting today. I look forward to the excitement of the next 25 years.

References

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