Part 2

From Molecular Clouds to Protostellar Cores

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Star Formation at High Angular Resolution
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Techniques of mm/sub-mm Interferometry in Star Formation

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Abstract. Since the earliest stages of star formation occur deep in clouds of gas and dust, they are hidden from optical view. Nevertheless, infrared and millimeter wavelength observations over the last twenty years have enabled increasingly detailed studies of the processes involved in stellar birth. High resolution, aperture synthesis imaging of the millimeter-wave radiation from dust and molecular gas in star-forming clouds has proven particularly effective. On the other hand, there can be pitfalls to be avoided in the use of mm/sub-mm interferometry techniques. Here, we consider what has been learned from currently-operating mm interferometers and the potential of the next generation of arrays.

1. Introduction

Observations at millimeter and sub-millimeter wavelengths are critical to understanding how stars are born. Star formation takes place in the cores of dense interstellar clouds of dust and molecular gas, preventing optical studies. However, at the low temperatures typical of these regions, $\ll 100$ K, dust continuum and spectral line radiation from many molecular species are prominent in the mm and sub-mm bands. Thermal emission from warm dust provides information on source morphology and mass, as well as grain properties. Spectral line emission can shed light on both the physical properties of the gas, particularly the nature of the velocity field, and its state of chemical evolution.

The spatial scales relevant to star formation studies range from around 100 pc to a few AU. In our Galaxy, this translates to tens of arc minutes for giant molecular clouds (GMCs), arc minutes for cluster-forming cores or the energetic bipolar outflows associated with low-mass protostars, and sub-arc second for protostellar envelopes and protostellar or protoplanetary disks. A similar range of scales is useful for observations of star formation in other galaxies. Typical angular sizes as a function of distance are summarized in Table 2 of the 1993 review of millimeter and submillimeter interferometry by Sargent & Welch, but illustrative examples can be found throughout this volume. Essentially, star formation studies are well served by observations that provide high sensitivity to small sources over a wide field of view.

At mm/submm wavelengths, these high sensitivity, high resolution requirements lead inevitably to the use of interferometric techniques. Since the surface efficiency of a telescope scales a $e^{-(4\pi\sigma/\lambda)^2}$, where λ is the relevant wavelength and σ the rms surface error in μm, σ should be low for telescopes designed for

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mm/submm observations. The 30-m diameter IRAM (Institute de Radio Astronomie Millimétrique) telescope routinely attains $11''$resolution observations at $\lambda = 1$ mm but the diameters of submm telescopes are constrained to be at most 12-m, unless active metrology corrections can be applied to keep the surface errors below 20 μm. For higher angular resolution at mm/submm wavelengths, arrays of such relatively small telescopes and aperture synthesis imaging techniques must be used. In principle, sensitivity then scales with collecting area (effectively the number and size of the telescopes/elements in the array) and angular resolution, λ/d, increases with d, the maximum separation of the array elements. Any smooth, large-scale structure is resolved out by the interferometer, a useful advantage for studies of small sources in extended emission regions.

2. Millimeter/Sub-millimeter Interferometers

The Owens Valley Radio Observatory (OVRO) and Berkeley-Illinois-Maryland Association (BIMA) arrays provided the first $\lambda = 3$ mm interferometric images in the early 1980s. Within a decade, the Nobeyama Millimeter Array (NMA) and the IRAM Plateau de Bure Interferometer (PdBI) were also operating successfully and, soon after, the VLA acquired a 7mm capability. Aperture synthesis imaging in the $\lambda = 1.3$ mm band also became a reality in the late 1980s. The current properties of the arrays are summarized in Table 1.

Table 1. Currently Operating MM Arrays

	BIMA	OVRO	PdBI	NMA	VLA
Location	California	California	France	Japan	New Mexico
Telescopes	10	6	6	6	28
Diameter	6m	10m	15m	10m	25m
Elevation	1043m	1216-m	2552m	1350m	2124m
Wavelength	3&1mm	3&1mm	3&1mm	3&2mm	7mm
Baselines	1km	440m	408m	560m	36km
Max^m Resolution	$0''.2$	$0''.4$	$0''.5$	$0''.8$	$''.05$

Results from these instruments have demonstrated that mm interferometer observations are vital to studies of star formation across the observable universe, from nearby in our Milky Way galaxy to epochs close to the end of cosmic reionization. The importance of achieving high resolution cannot be underestimated. Nevertheless, there are technical pitfalls inherent in mm/submm interferometry. The more important are summarized below. Further details can be found in the review of mm interferometry by Sargent & Welch (1993).

The effective sensitivity of an interferometer array depends not just on the size and number of elements involved but also on the bandwidth. While increased bandwidth has most obvious benefits for sensitivity to dust continuum, emission, it is also important for spectral line correlators to ensure adequate velocity coverage at mm/submm wavelengths. Briefly, at $\lambda = 3$ mm, 1 MHz of bandwidth is equivalent to velocity coverage of only about 3 km s^{-1} and the situation becomes progressively worse with decreasing wavelength. Efforts to

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increase available correlator bandwidth are ongoing and, very recently, a 4 GHz correlator has been introduced at the OVRO array.

The limited field of view (FOV) of an interferometer can also be problematic. Arrays of telescopes readily provide high resolution observations of sources smaller than the full width half maximum (FWHM) size of the primary beam, $\approx \lambda/\mathrm{D}$, where D is the telescope diameter. For an array of 10-m telescopes, the FWHM primary beam, or FOV, is $\sim 60''$ at 3 mm and $\sim 30''$ at 1.3 mm. Observations of sources larger than the primary beam must be covered by multiple pointings of the interferometer, and subsequent combination of these pointings in a mosaic. Mosaicing places strong constraints on telescope design since pointing accuracy and reliable calibration are critical. Typical pointing requirements are for $\sim 1''$ accuracy at $\lambda = 1$ mm, with concomitantly more stringent demands at submm wavelengths. Moreover, the sensitivity of an interferometer to extended sources is effectively reduced by the small FOV and resultant need for mosaicing, unless compensated for by the addition of more elements.

As already noted, interferometers filter out emission from any continuous structure that is larger than the FWHM primary beam of the individual telescopes. Thus the total flux from an extended source may not be recovered. Interferometric images can also be seriously distorted as a result of gaps in the visibility coverage, particularly at the origin of the visibility plane (in effect the antenna separation (or *uv*) plane). The requisite data to fill this gap at the origin would come from telescopes placed only one diameter apart and is often referred to as “zero-spacing flux”. It is possible to compensate for the missing flux by adding data from maps of the source made with a telescope of at least twice the diameter of one of the interferometer elements but this requires considerable allocations of time on highly competitive instruments. Ideally, the additional data can be acquired from a co-located array of smaller telescopes.

Finally, it is clear that fluctuations in the water vapor column above each telescope in an array result in atmospheric phase variations. This radio form of “seeing” in turn causes decorrelation and limits the sensitivity and dynamic range of mm-interferometer maps. The problem is worst at the highest resolutions when separations of the array elements greatest. Efforts are under way at a number of observatories to develop methods of measuring and correcting for these phase variation so that the highest theoretically attainable resolution can be realized (e.g. Woody, Carpenter & Scoville 2000).

For the next generation of mm/submm interferometers, it is important to ensure that the difficulties identified above are minimized. More immediately, it is important to access the southern sky and frequencies between 350 and 850 μm that are as yet unexplored at high resolution. Properties of the newest mm/submm arrays are displayed in Table 2. Observations with the Smithsonian Sub-millimeter Array (SMA) and the Australia Telescope Compact Array (ATCA) have already begun. The Combined Array for Research in Millimeter-wave Astronomy (CARMA), comprising the six 10-m OVRO antennas and nine of the 6-m BIMA antennas on a higher elevation site, should be operational in 2005. Construction of the Atacama Large Millimeter Array (ALMA) has begun and should be completed by 2012, although observing with subsets of the final quota of telescopes is expected to begin in late 2007.

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Table 2. New MM/Submm Arrays

	SMA	ATCA	CARMA	ALMA
Location	Hawaii	Australia	California	Chile
Telescopes	8	3(5) m	6+9(+8)[a]	64
Diameter	6m	22m	10m+6m(3.5m)[a]	12m
Elevation	4080m	200m	2300m	5010-m
Wavelength	1mm-350μm	12&3mm	1&3mm	1mm-350μm
Bandwidth	2GHz	2GHz	4GHz	16GHz[b]
Baselines	508m	to 3km	2km	to 14 km
Resolution	$0''.1$	$0''.5$[c]	$0''.1$[c]	$0''.02$[c]

[a] additional 8 antennas from University of Chicago Sunyaev Zel'dovich array
[b] assumes dual polarization capability
[c] with phase correction scheme in place

Each of the instruments in Table 2 has new or enhanced capabilities compared to the existing interferometers. The SMA and ATCA are opening new windows in star formation research, the former by enabling the exploration of the submm wavelength band down to 350 μm at high resolution and the latter by providingthe first access to high resolution mm studies of the southern sky. For CARMA, the increased number of telescopes (15) and baselines (105), higher elevation location, and larger bandwidth, together with an atmospheric phase correction scheme, should improve sensitivity and imaging fidelity by an order of magnitude compared to the current BIMA and OVRO arrays. The heterogeneous complement of telescopes provides the potential for wide-field, high resolution, high dynamic range mapping. It will also be possible to recover "missing" flux on all scales, especially in the longer term when eight 3.5-m telescopes of the University ofChicago's Sunyaev-Zel'dovich Array become part of the instrument. ALMA which is being constructed under a bipartite agreement between Europe and North America will dwarf all preceding arrays by many orders of magnitude in sensitivity, imaging speed and fidelity. It will also access the southern sky and provide important observations to complement those made with ESO's VLT and the proposed James Webb Space Telscope (JWST). Nevertheless, atmospheric phase correction will be still be critical to realizing the highest resolution, and a means of recovering missing flux will be critical. It is very likely that this can be accomplished by way of an array of twelve 7m telescopes, the Atacama Compact Array (ACA) to be provided by Japan and located close to ALMA. Japan also proposes to contribute additional ALMA receivers to increase submm wavelength coverage.

3. Illustrative Scientific Results

Despite the challenges, the existing mm arrays have made major contributions to our understanding of how stars form and provided the scientific justification for the new instruments. The sample of results presented below were selected not just to demonstrate the power of interferometry for star formation studies

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but to highlight some of the driving factors in defining the arrays that are now becoming operational or are under construction.

3.1. Star Formation in the Early Universe

A relatively recent but particularly exciting area for mm/submm interferometry star formation research involves the population of distant dust-rich galaxies revealed in deep submm (850 μm) surveys carried out at the James Clerk Maxwell telescope using SCUBA (e.g. Smail et al. 1997, 2002; Cowie et al. 2002; Ivison et al. 2002). It is often difficult to identify optical counterparts and establish redshifts unambiguously from the relatively low resolution ($\approx 15''$) SCUBA images. However, accurate redshifts and positions can be determined with sensitive, high resolution, molecular line interferometry, since the CO emission will be shifted to mm and even cm wavelengths if, as expected, these galaxies lie at very high redshifts. Indeed, CO imaging programs with the OVRO and Plateau de Bure arrays, with resolution $\sim 3''$ have now provided redshifts for five such galaxies (Frayer et al. 1998, 1999, 2003; Neri et al. 2003). Values of z range from 2.4 to 3.4, and the large quantities of gas detected support the hypothesis that the high submm fluxes are powered predominantly by star formation. A dramatic demonstration of the effectiveness of interferometer measurements of the high-z universe come from the very recent detection of molecular gas at z=6.42 in SDSSJ1148+5251 (Walter et al. 2003; Bertoldi et al. 2003), a luminous infrared galaxy identified in the IRAM/MAMBO (Max-Planck Millimeter Bolometer) survey at 1.2 mm. The subsequent CO detection relied on a combination of the high spatial resolution of the VLA ($1.8''\times 1.5''$) at 7 mm and the high spectral resolution of the PdBI at 3 mm.

Sensitivity is the key to expanding this program to a larger sample of the submm population of galaxies. ALMA, with much greater collecting area and broad bandwidth on a very high elevation site, will at last enable CO surveys at high resolution. (One driver for ALMA was the desire to detect a galaxy at $z = 3$ in less than 24 hrs.) In the near term, CARMA, with more modest enhancements, can contribute, but only object by object. CARMA imaging of the thermal dust emission *perse* from these high-z objects does however look promising. Continuum emission from a galaxy at z=2.56 has been already been detected with the OVRO interferometer and the new 4 GHz bandwidth COBRA (Caltech-OVRO Broadband Reprogrammable Array) correlator (Hainline & Scoville 2004).

3.2. Giant Molecular Clouds in Nearby Galaxies

The higher resolution afforded by mm interferometers makes possible unbiased surveys of GMCs in a range of environments to determine the role of kinematics, gas surface density, metallicity, pressure, radiation field, density waves, and their effect on the rate at which GMCs form massive stars. The results of such studies have wide-ranging implications and can for example lead to a better understanding of the CO-to-H_2 ratio (the so-called **X**-factor) that is used to determine H_2 masses of galaxies. Compared to the primary beam size of the existing mm arrays, nearby galaxies are, of course, extended sources and images require mosaicing, with all its attendant problems. Nevertheless a successful CO(1-0) map of M33, at $13''$ resolution (50 pc) and comprising 800 pointings, has recently

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been acquired with the BIMA array (Engargiola et al. 2003). Almost 150 separate clouds have been identified. HII regions, implying recent star formation, are seen at galactic radii far beyond the observed extent of CO, suggesting more clouds exist beyond the current sensitivity limit. The **X**-factor appears to be insensitive to metallicity and shows no gradient across the galaxy. Systematic measurements of the angular momentum of the GMCs indicate that this can be 10-100 times lower than values typical of the gas from which they formed and is interpreted as evidence for angular momentum loss even the earliest stages of star formation. The total mass of GMCs detected is $2.3\times10^7 M_\odot$. However, as explained earlier, interferometers act as spatial filters. To account for any missing flux, single dish observations were made with the UASO 12-m telescope, leading to a value of $4.5\times10^7 M_\odot$ for total mass of molecular gas in M33. With CARMA, and even more with ALMA, it will be possible to extend studies like this to beyond the Local Group and to a wider variety of galaxies types. The mix of telescope sizes in the CARMA array and the ACA with ALMA provide a straightforward way of compensating for missing flux.

3.3. Star Formation in our Galaxy

Spatial filtering by interferometers can be very useful for studies of star-forming cores. Although it is commonly agreed that most stars are born in groups or clusters, details of how the star formation proceeds and what factors control the Initial Mass Function (IMF) are not yet clear (e.g. Shu et al. 1993). With an interferometer, individual protostellar condensations can be identified, even although they are located in regions of low-level extended emission, allowing studies of the formation and evolution of pre-stellar condensations. Thus, an OVRO array image of a $5' \times 5'$ region in the Serpens core (Testi & Sargent 1998) suggests that the mass spectrum of the small scale dust condensations is similar to the field star IMF, and significantly different from the mass spectrum of gaseous clumps in molecular clouds. A similar result has been derived for the ρ Ophiuchi core (Motte, André, & Neri 1998). If this is the case in general, turbulent fragmentation may be the determining factor for the low mass end of the IMF (e.g. Myers 1998).

Observations of many more star-forming cores are clearly necessary to confirm this hypothesis. High resolution CARMA mosaics will be able to survey cluster-forming cores with much lower mass limits than have hitherto been attained. Sensitivity of 1 mJy/beam at 1.3 mm over a $5' \times 5'$ field will be reached in only 1 transit, an order of magnitude better than the Serpens study. Protostellar condensations down to 0.03 $M_\odot$ should be detectable and will enable empirical determinations of the pre-stellar IMF. Its mix of telescope sizes make CARMA particularly suitable for such high resolution studies of extended regions. The vastly better sensitivity and imaging power of ALMA, will of course, extend the sample to sources throughout the Galaxy but compensating short-spacing data from the ACA will be vital.

A dramatic example of how the interpretation of interferometer observations of extended star forming regions in the Galaxy can be complicated, even when short spacing flux information is available, is provided by Plambeck & Wright (2001). As they point out, high resolution (to $0''.26$) images of the gas and dust around the T Tauri star, HL Tau, from the OVRO, NMA, and BIMA

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arrays have been interpreted as evidence for the presence of a circumstellar disk (Sargent & Beckwith 1987, Hayashi, Ohashi & Miyama 1993, Mundy et al. 1996, Looney, Mundy & Welch 2000). On the other hand, in PdBI images, gas appears to be expanding away from the star (Cabrit et al. 1996). Support for this interpretation comes from a 7-field, 7″ resolution, BIMA array mosaic (including short spacing fluxes from the NRAO 12-m telescope) of the ^{13}CO emission over a 3′× 3′ field centered on HL Tau. This suggests that the observed emission is merely part of a larger expanding shell, perhaps produced by the wind from the nearby star, XZ Tau (Welch et al. 2000). However, unpublished, 2″ resolution, OVRO array images of the ^{13}CO (2-1) emission from HL Tau show *both* a flattened blueshifted component compatible with the PdBI and large-scale BIMA maps, and a much more compact, redshifted component that corresponds well with the HL Tau dust disk observed at high resolution by Looney et al. (2000). Only the high resolution, high sensitivity extended field observations that can be obtained with the new arrays can resolve this dilemma.

3.4. Interferometry of Protoplanetary and Protostellar Disks

High resolution mm/submm measurements of the kinematic and chemical properties of protostellar and protoplanetary disks are critical to obtaining a better understanding of their evolution. This is particularly the case since these disks are likely to hold clues as to how our own and other planetary systems formed and evolved. State of the art examples in this field are provided by several other contributions in this volume. Note especially those by Wilner and collaborators for new SMA results, Dutrey and collaborators for PdBI, Wong and collaborators for ATCA. The new SMA images are especially tantalizing and indicate the enormous amount of information on different molecular species that waits to be mined. Likewise the first mm images of disks from ATCA (Wilner et al. 2003) merely hint at the broad spectrum of new southern star formation regions that will now be accessible to high resolution mm/submm observations.

High resolution mm/submm mosaics of extended fields, with all the associated advantages and disadvantages already described, are also needed to examine the behavior of disks in different environments. Eisner & Carpenter have carried out pioneering studies in this area and shown how these can provide a measure of disk lifetimes and masses in clusters. Their map of a 2′.5 × 2′.5 region of the cluster NGC 2024 in the 3 mm dust continuum emission, for example, demonstrates that only 6% of young stellar objects in this $\sim 3{\times}10^5$ yr-old cluster show evidence for the presence of circumstellar disks with masses greater than 0.06 $M_\odot$, although the many detected K-band sources (Meyer 1996) may support lower mass ($\sim$ 0.005 $M_\odot$) disks. A comparison of these results with a similar study of the older cluster IC 348, $\sim 2 \times 10^6$ yrs, where the average disk mass appears to be a factor of 2.5 lower, suggests that the disks evolve on 10^6 yr time scales. Massive disks appear to be rare in the cluster environment, compared to the Taurus cloud. Obviously studies of this kind have important implications for the conditions necessary for planet formation. Only a few clouds have been sampled to date, even in the infrared (e.g. Haisch et al. 2001) and with increased sensitivity, the high resolution mm/submm can be extended to a wider variety of clusters.

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3.5. Debris Disks

The opportunities to study the circumstellar environments of older stars will increase rapidly with the advent of the new arrays. These A stars are sufficiently old, $\geq$ a few *times* 10^7 yrs, that it seems likely that planets have already formed and the detected dust disks are composed of the detritus of the formation process (see Lagrange et al. 2000). Since the debris disks with strongest mm/submm emission lie mostly in the southern sky (see Holland et al. 1998), to date, only Vega has been observed with mm interferometers (Koerner, Sargent, & Ostroff 2001, Wilner et al. 2002). The results are intriguing and appear consistent with the presence of a cleared area of radius $\sim$ 80 AU around the star, presumed to be due the presence of a planet, and an azimuthally asymmetric dust torus rather than a disk. Wide field, high resolution, submm interferometry is necessary to make headway in understanding these disks. It is anticipated that SIRTF will also detect a range of new debris disk candidates for observation. Very recent observations with the JCMT/SCUBA and the OVRO array indicate that even G stars may support disks (Williams et al. 2003, Carpenter 2003, private communication)

4. Summary

The scientific results presented here represent only a small fraction of the star formation science currently being carried out using mm/submm interferometer techniques. Other articles in this volume provide further examples. In particular, the importance of high resolution imaging in investigating the origin and evolution of energetic bipolar outflows is made very obvious in a recent OVRO survey (Arce 2003). As Crutcher (2001) describes so well, high resolution observational information on magnetic fields is critical to understanding how stars are born. While CARMA will make some inroads, ALMA's dramatic increase in sensitivity, coupled with its polarization receiver complement, will revolutionize this area of study. Numerous other articles in "Science with the Atacama Large Millimeter Array (ALMA)" (Wootten 2001) also attest to the potential of mm/submm interferometry.

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