

## Aperture Synthesis Spectral Line Imaging: Exploring the Third Dimension

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### Abstract.

Radio astronomers are in a privileged position as compared to optical and near-IR observers because almost from the beginning of radioastronomical observations it proved possible to obtain spectral information at velocity resolutions of order of several  $\text{km s}^{-1}$ . Currently, single dish telescopes equipped with multi-beam receivers, scanning the sky “on the fly”, fitted with powerful digital backends (digital autocorrelators) or aperture synthesis telescopes doted with even more impressive digital crosscorrelators routinely collect stunning 3D images across the radio window, from (sub)mm all the way to meter wavelengths. In this talk I will give a summary of some of the characteristics of the world’s most powerful radio telescopes, show some examples of state-of-the-art radio observations as applied to studies of the ISM in nearby (dwarf) galaxies, and refer to some of the radio telescopes of the future, such as the LMT, ALMA and the plans for a Square Kilometer Array (SKA).

### 1. Introduction

Many, if not most of the presentations during this conference, have focussed on the impressive progress which has been made regarding optical/NIR instruments for obtaining 3-dimensional (position-position-velocity) maps of the sky. One should not forget, though, that at the long wavelength end of the electromagnetic spectrum radio astronomers have been in the business of instantaneous 3D mapping for decades! This is especially true for studies in the lines of HI, OH, and CO, but in reality this applies to any spectral line that is being mapped in radio.

In what follows I will review which techniques are currently at the disposal of the astronomical community, dealing with single dishes as well as radio interferometers. This will be followed by some examples of recent results of the study of the ISM in nearby galaxies, in order to stay within the main topic of this conference.

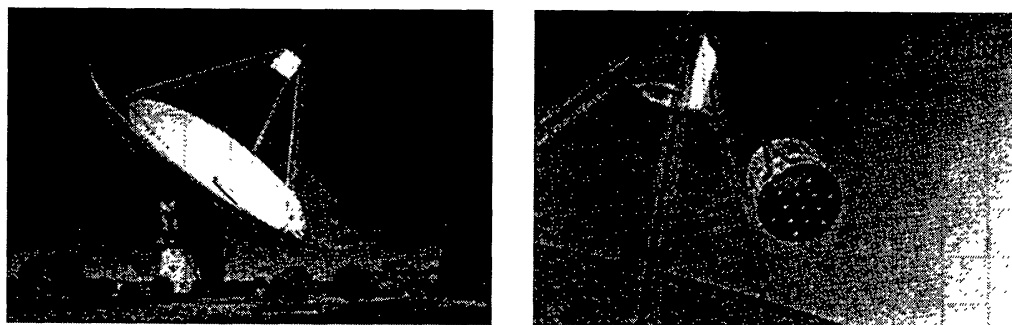


Figure 1. Image of the 64-m Parkes Radio Telescope (Australia) on the left; on the right the multi-element front-end is seen being hoisted up to the prime focus box (photos courtesy John Sarkissian, CSIRO Parkes Observatory).

## 2. Single Dish Radio Telescopes

For almost half a century, single-dish radio telescopes, were at best 1D detectors, with which, at any one moment, one could obtain a spectrum along a single line-of-sight. Clever mapping schemes, such as basket-weaving (later refined by the adding of scans in Fourier space to remove gain variations, either due to the instrument or atmosphere), allowed mapping of areas on the sky, building up a data cube. However, the cube was basically still obtained by combining data on a point by point basis. A technical improvement over basket-weaving has been the implementation of “on the fly” mapping, in which the single dish telescope beam scans a certain area rapidly while data are continuously read out.

In fact, a single dish telescope is not unlike a one-channel photometer in the optical, except that one can obtain at any one moment a high quality, high resolution spectrum. For example, with a digital autocorrelator one can routinely sample a  $10000 \text{ km s}^{-1}$  range at better than  $10 \text{ km s}^{-1}$ , or at the flick of a switch, a  $10 \text{ km s}^{-1}$  range at  $10 \text{ ms}^{-1}$ , for that matter. The fact that radio astronomers have the edge over their optical colleagues when it comes to spectral resolution is, of course, due to the nature of radio waves which, at wavelengths between, say 0.2 and 60 cm have low frequencies, of between  $0.5$  and  $150 \times 10^9 \text{ Hz}$  rather than the  $3 \times 10^{13}$  to  $3 \times 10^{15} \text{ Hz}$  range, typically encountered in the optical/NIR. This low frequency makes filtering and other manipulation far easier.

It is only a few years ago, though, with the advent of multi-beam receivers, that single dish telescopes have ventured into the realm of true, instantaneous 3D mapping. Examples at centimeter wavelengths are the 13-feed prime focus box installed at the Parkes 64-m antenna (see Figure 1), which has been key to the success of the HIPASS survey (Barnes et al. 2001) and a nine-element clone installed at Jodrell Bank at the Lovell telescope. These multibeam instruments are analogous to a CCD of a few  $\times$  a few pixels, with the advantage that each pixel is fed into an autocorrelator to give a high resolution spectrum. These instruments thus truly produce an instantaneous datacube, albeit that the sampling in the spatial directions is incomplete and one would in practice want to

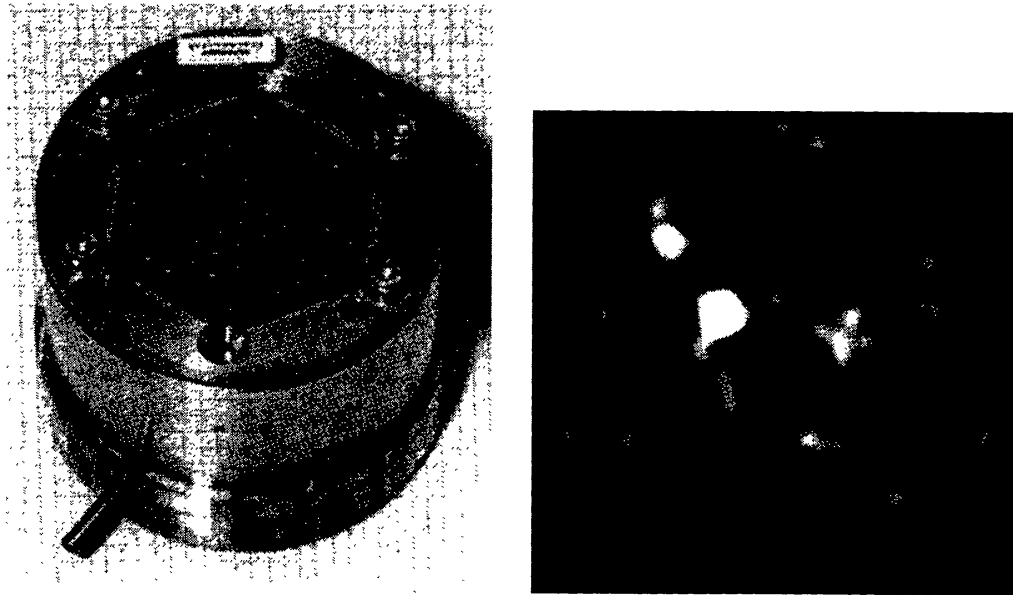


Figure 2. Picture of the short wavelength SCUBA multi-element array (courtesy Joint Astronomy Centre) on the left and on the right the Hubble Deep Field as imaged with SCUBA at  $850\ \mu\text{m}$  (Hughes et al. 1998).

step the multiple beam across the sky to fully sample (in the Nyquist sense) the spatial coordinates, building up a complete datacube of the object under study.

At millimeter and submillimeter wavelengths it is possible to squeeze more feed horns (or detectors and hence pixels) within the focal plane than is possible at longer wavelengths, hence there now exists a  $2 \times 16$  element array, SEQUOIA (at the FCRAO 14-m dish) and a 37 element array known as MAMBO (on the IRAM 30-m telescope), whereas at submillimeter wavelengths SCUBA on the JCMT fits 37 pixels at  $850\ \mu\text{m}$  and 91 feeds (or pixels) at  $450\ \mu\text{m}$  (see Figure 2).

Although single-dish radio telescopes have become true 3D imagers, there is one limiting factor which is, of course, the fact that their resolution, especially at centimeter wavelengths, is poor. For example, even an impressive 100-m radio dish such as Effelsberg, or the Green Bank Telescope (GBT) manages a modest  $9'$  beam when observing the 21-cm line of neutral hydrogen (HI). Although this might be acceptable for Galactic work, higher resolution is needed for extragalactic projects. The obvious answer to the question how to improve upon the limited performance as far as angular resolution is concerned is to go for radio interferometry instead.

### 3. Radio Interferometers

Aperture synthesis interferometers, as I will explain in a moment, are intrinsically 2D detectors. In fact, they are not unlike optical CCDs, but more flexible in the sense that *after* the observation one can manipulate the parameters of the CCD, choosing the area to be imaged and the pixel size. Moreover, instead of just measuring the total power, one can obtain instantaneously for each pixel a

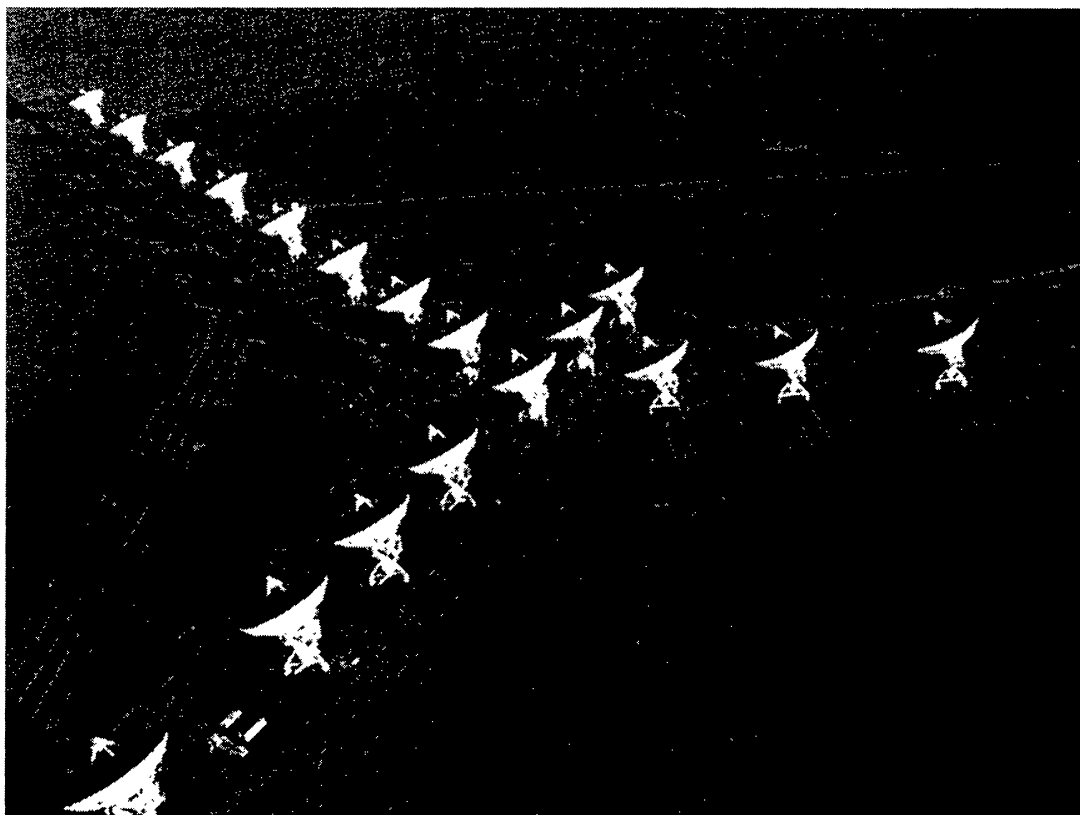


Figure 3. Bird's eye view of the NRAO Very Large Array (courtesy Dave Finley, National Radio Astronomy Observatory and Associated Universities, Inc.).

spectrum, with the resolution and spectral coverage limited by the speed of the electronics in the complex crosscorrelator. In this case we're talking about maps of, for example  $1024 \times 1024$  pixels, each pixel being 512 spectral channels deep.

Examples at centimeter wavelengths are the Westerbork Synthesis Radio Telescope (WSRT), the NRAO Very Large Array (VLA; Figure 3), and the Australia Telescope Compact Array (ATCA), to name but a few. At millimeter wavelengths, the existing instruments are the Owens Valley Radio Observatory (OVRO) array (Figure 4), the Berkeley–Illinois–Maryland Array (BIMA), the Plateau de Bûre interferometer operated by IRAM, and the Nobeyama array. The future for millimeter astronomy is particularly bright with OVRO and BIMA planning to merge their arrays to form CARMA, putting their telescopes together on a superior site, and with ALMA which is to be built in Northern Chile.

For those unfamiliar with the tremendous power of aperture synthesis spectral line imaging, I'll try to sketch in broad terms what can routinely be achieved these days. An array usually consists of as many telescope as funding allows. The VLA consists of 27 telescopes whereas ALMA is planned to have 64 telescopes. In aperture synthesis, the interferometry is done between pairs of telescopes, giving at any moment  $N(N - 1)/2$  pairs where  $N$  is the number of antennae in the array. Each pair acts like the equivalent of a double slit experiment in the



Figure 4. The millimeter array of the Owens Valley Radio Observatory (courtesy OVRO, California Institute of Technology).

optical, measuring the brightness of the sky (known as visibility) convolved with a fringe pattern which is defined by the distance and orientation (better known as baseline) between telescopes. As each telescope pair measures the same patch of sky but convolved with a different fringe pattern, a large number of visibilities, each corresponding to a characteristic spatial frequency, is collected. The Fourier transform of these visibilities corresponds to a map of the sky.

This is analogous to displaying the sound produced by, e.g., a vibrating string on an oscilloscope (intensity as a function of time) and using a spectral analyzer to determine the intensity of each harmonic (the intensity as a function of frequency). Once all harmonics are known, one can reconstruct the original sound or intensity as a function of time, the two renditions of the same information being linked by a Fourier transform.

The size of the image which is built up depends of course on the patch of sky which is visible to each of the individual elements, i.e., it is set by the beam size, at the wavelength employed, of the individual (“single”) dishes which make up the array. The sensitivity within the field imaged drops off gradually from the center outwards and one usually limits the analysis to the full width at half maximum of the beam of an individual element, known as the primary beam. The beam size of the combined array is referred to as the synthesized beam.

One of the trade-offs in the design of an interferometer is the desire for a large field-of-view, which implies small individual elements, and instantaneous high signal-to-noise, which calls for large elements. Of great advantage is that an interferometer changes its orientation with respect to the sky, allowing it to sample a range of spatial frequencies in the course of, say, a 12-hour shift, continuously building up the components of an image of the sky. Despite the fact that this method of aperture synthesis allows one to build up an almost perfect image as if it were taken by a much larger diameter dish, the fact remains that this is achieved by smallish individual elements which ultimately limits the sensitivity. Without going into too much detail, it should be noted that interferometers are like spatial filters and that spatial scales larger than that corresponding to the smallest distance between two telescopes cannot be retrieved on the basis of interferometry alone (this is known as the missing short-spacing problem). In other words, an interferometer is blind for extended structures. Also, the total flux of a field has to be arrived at via some iterative process (the flux over the entire sky as observed by an interferometer being by definition zero). The few drawbacks, or rather complications inherent to interferometry, are offset by the vastly superior spatial resolution, improved gain stability, and reduced susceptibility to interference.

In a manner analogous to producing an autocorrelation spectrum, the digitized signal of one telescope is correlated with that of another (a process better known as crosscorrelation). This leads to an instantaneous spectrum, the resolution and wavelength coverage being limited by the electronics. Over time the correlators have become ever more powerful and flexible, with no limit in sight, allowing velocity coverage at a few  $\text{km s}^{-1}$  over thousands of  $\text{km s}^{-1}$  velocity range.

#### 4. HI and CO Observations

During this meeting many authors showed velocity fields based on 3D optical techniques, such as Fabry–Perot imaging in the line of  $\text{H}\alpha$ . Although for certain applications where resolution is the main driver, these data are important, I think it is fair to state that HI imaging of the 21-cm line is invaluable when dealing with the global velocity field as HI is by far the best tracer we have for the cool interstellar medium (ISM) in galaxies. Compared to  $\text{H}\alpha$ , it has a far smoother distribution and extends much further out, sometimes up to twice the Holmberg radius. Besides, it *indirectly* reveals those regions which are thought to be filled with coronal gas (superbubbles). In fact, without HI (and CO) data one gets an incomplete view, at best, of the morphology and composition of the ISM. The best of both worlds is obtained, of course, when combining radio and optical 3D data, as has been done successfully by Blais–Ouellette et al. (2001).

Given the fact that this meeting was designed to address two issues, 3D imaging in all its aspects, and the application of 3D imaging to galaxy research, I will illustrate some of the statements made above using the data on two interesting galaxies, both members of the nearby M 81 group, i.e., the dwarf irregular IC 2574 and the prototypical starburst galaxy M 82. Another, truly stunning example of what can be achieved at yet higher (linear) resolution has been pre-

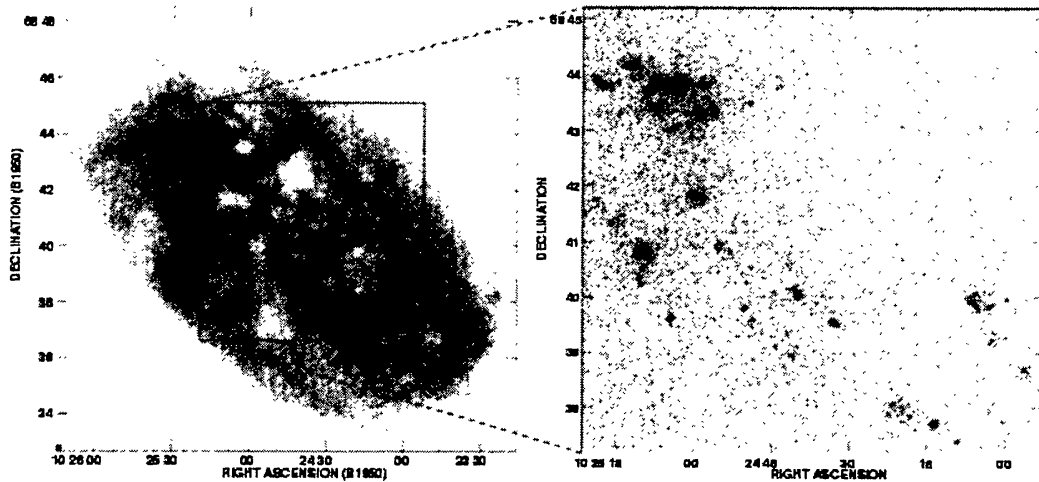


Figure 5. Integrated HI surface brightness map from Walter & Brinks (1999) displayed as a grey scale image on the left hand side. To the right is shown the  $H\alpha$  emission corresponding to the area enclosed by the larger box. The smaller dotted box corresponds to the area highlighted in Figure 6.

sented by Staveley-Smith et al. (1997) and Kim et al. (1998) in the form of HI maps of the Magellanic Clouds (Points 2002).

#### 4.1. IC 2574

Figure 5 shows an image in  $H\alpha$  side-by-side to a picture of the total HI surface brightness map of IC 2574. Please notice the almost fractal nature of the HI distribution and the presence of large scale filaments and features such as supergiant shells. Compared to the HI map,  $H\alpha$  emission presents quite an incomplete picture of the morphology of the ISM. On the smallest scales,  $H\alpha$  is superior to HI data, though, due to its higher angular resolution (in the radio, HI observations can reach  $6'' - 10''$  whereas in the optical the seeing, of about  $1''$  is the limit), and shells and bubbles blown by individual supernovae can be traced.

It is difficult to convey in print (and certainly in black and white) the full information content of a typical HI data cube. Figure 6 makes an intent by showing a sequence of channel maps (position-position maps at a range of velocities) represented as a mosaic (the area shown is indicated by the dotted box in Figure 5). Similar data can also be used to cut through the data cube, the most useful being generally the cuts made along lines parallel to the major or minor axis. These plots are known as position-velocity (or pV) maps and are not unlike optical long-slit spectra.

For those struggling to visualize data cubes, a particularly powerful package to roam through 3D space, originally developed for radio data, is known as KARMA which was developed by Richard Gooch (1996).

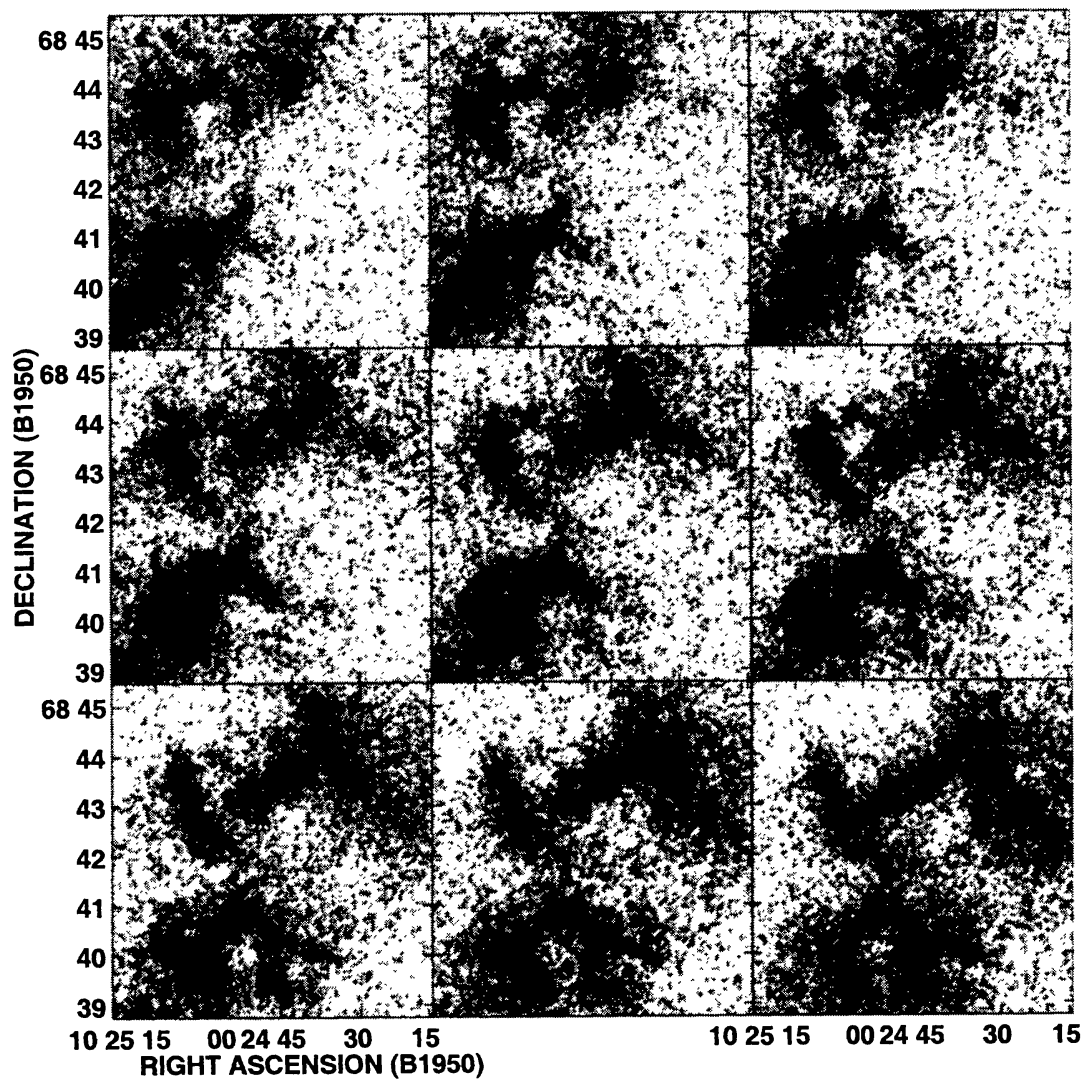


Figure 6. Individual channel maps showing the HI emission within the area of the dotted box outlined in Figure 5. The heliocentric velocity in  $\text{km s}^{-1}$  is indicated in the top right part of each channel. Please note the presence of numerous superbubbles and supergiant shells.



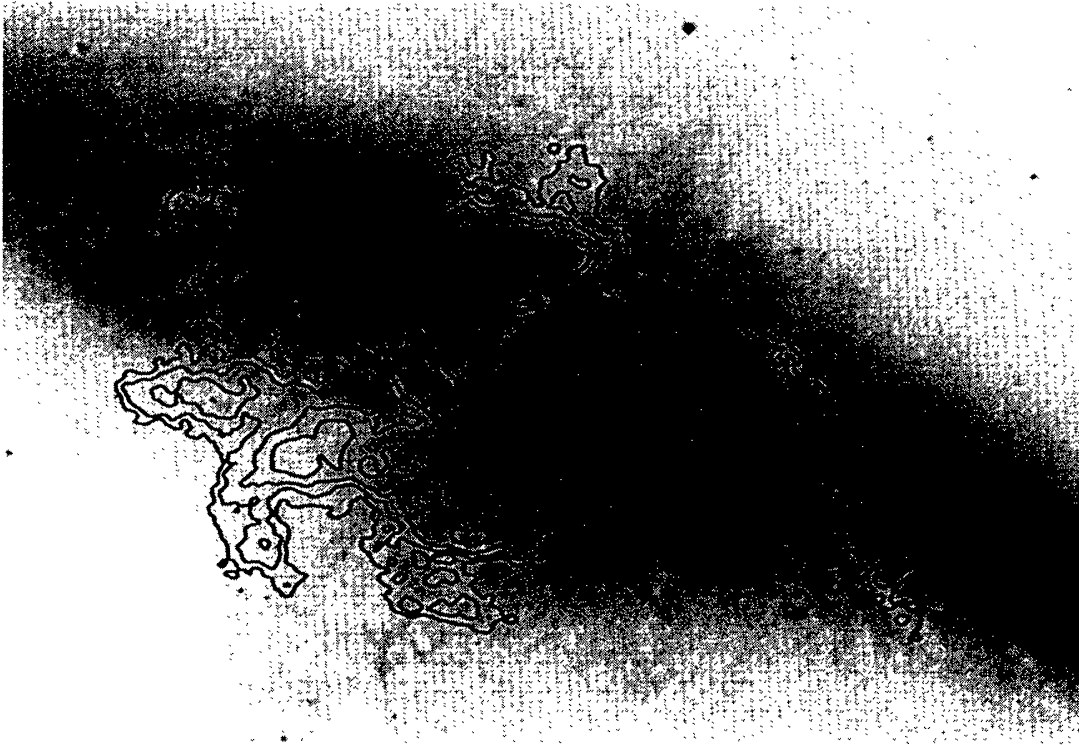


Figure 7. The prototypical starburst galaxy M82. The grey scale is a representation of an optical image (area shown:  $\sim 4 \times 3$  kpc). The contours show the distribution of the molecular gas in this galaxy (CO(1-0) OVRO mosaic).

#### 4.2. M 82

In order to show what can be done currently with millimeter interferometers, I will in this section show some recent results on M 82, a nearby starburst galaxy. Figure 7 shows the first wide-field, high-resolution map of the molecular gas in M 82 covering an area of  $2 \times 3$  kpc<sup>2</sup>, obtained with the OVRO millimeter interferometer in the CO(1-0) line. The new observations include parts of the prominent outflow as well as some of the tidal features around this heavily interacting galaxy. The OVRO observations reveal a striking amount of structure in the molecular medium: tidal features are clearly visible and molecular gas is found to be associated with the extreme outflow seen in H $\alpha$  and X-rays. This spectacular view on the molecular properties gives new insights on the processes that lead to the extreme starburst properties in M 82 (Walter, Weiss & Scoville 2002).

### 5. Summary and Future Developments

Instantaneous 3D imaging at radio wavelengths has been with us for decades and has led to important results and discoveries. An early milestone certainly was the complete mapping of the HI in our Galaxy (van de Hulst et al. 1954). Nowadays, studies of the ISM have been extended to (nearby) galaxies, as the two examples



Figure 8. ALMA conceptual image courtesy of the European Southern Observatory (ESO).

given above amply illustrate. HI observations are simply indispensable when studying the distribution of the cool phases of the ISM. And as shown in Figure 5, the HI delineates large-scale structures such as superbubbles which might be filled with coronal gas.

HI observations have also played a pivotal role in determining the dynamical mass of galaxies, firstly because the HI extends further out than other tracers which can be used to probe the velocity field, such as HII regions. Secondly, HI velocity maps are often the only way to unambiguously determine the inclination of a galaxy. In short, HI maps have been instrumental in demonstrating that more than 90% of the inferred dynamical mass is in a form which to this date has remained invisible, the dark matter.

Another fundamental contribution of HI imaging has been in the field of interacting galaxies. As the HI extends farther out than the light and hence is gravitationally less bound, it is more susceptible to the effects which interactions impose. Objects which in the optically look apparently undisturbed often reveal, under closer scrutiny in HI, bridges, tails, optically faint companions, or even counter-rotating gas disks, all manifestations of gravitational interactions. A nearby striking example is the M 81 group (Yun et al. 1994).

Lately, HI observations have been hitting a hard limit, though, which is set by the intrinsically low surface brightness of the 21-cm line. As a result, it has proven hard to improve upon the canonical  $6'' - 10''$  angular resolution. The only way out is to enlarge the collecting area. This will be one of the many

benefits which will be provided by the Square Kilometre Array (SKA), an array which will have a collecting area some 75 larger than the VLA.

At (sub-)millimeter wavelengths, single dish telescopes equipped with multi-element receivers such as SCUBA-2 on the JCMT, which will have of order of 25000 pixels, have a bright future, delivering true, instantaneous 3D data efficiently. For example, the Mexican/US initiative to build a 50-m diameter Large Millimeter Telescope (LMT) equipped with SEQUOIA (and its successor) will lead to high sensitivity maps at  $^{12}\text{CO}(1-0)$  of  $10''$  resolution, comparable to the best HI maps currently available.

Millimeter interferometry is more or less where centimeter radioastronomy was in the sixties and early seventies, with modest arrays sporting half a dozen of elements. A major step forward will be the integration of the OVRO and BIMA telescopes on a better site, a project known as CARMA. At submillimeter wavelengths, interferometry is still in an experimental stage with the Submillimetre Array (SMA), an 8-element array being under construction on Mauna Kea.

The *pièce de résistance* for millimeter and sub-millimeter science will be ALMA, of course, an ambitious project about to become reality. With its planned 64 dishes it will have a 3.5 larger collecting area than the LMT and up to 200 its resolution (Figure 8).

So, although our optical colleagues are making valiant attempts to leave “flatland” and enter 3D space, radio astronomy, at least for the time being, has reached a technological limit, it seems that the future for radio astronomy and especially radio interferometry, is bright, a development which will no doubt lead to many more fascinating new results and discoveries.

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## References

- Barnes, D.G., Staveley-Smith, L. et al. 2001, MNRAS, 322, 486  
 Blais-Ouellette, S., Amram, P. & Carignan, C. 2001, AJ, 121, 1952  
 Gooch, R. 1996, in Astronomical Data Analysis Software and Systems V, eds. G.H. Jacoby and J. Barnes, eds., ASP Conf. Ser., 101, 80  
 Hughes, D.H., Serjeant, S. et al. 1998, Nature, 394, 241  
 Kim, S., Staveley-Smith, L., Dopita, M.A., Freeman, K.C., Sault, R.J., Kesteven, M.J. & McConnell, D. 1998, ApJ, 503, 674  
 Points, S. 2002, this volume  
 Staveley-Smith, L., Sault, R.J., Hatzidimitriou, D., Kesteven, M.J. & McConnell, D. 1997, MNRAS, 289, 225  
 van de Hulst, H.C., Muller, C.A. & Oort, J.H. 1954, Bull. Astron. Inst. Netherlands, 12, 117  
 Walter, F. & Brinks, E. 1999, AJ, 118, 273  
 Walter, F., Weiss, A. & Scoville 2002, ApJ Letters, submitted  
 Yun, M.S., Ho, P.T.P. & Lo, K.Y. 1994, Nature, 372, 530