Radio Astronomy: Visions for the 21st Century

Report of the Scientific Organizing Committee to the National Research Council

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The Workshop

The workshop *Radio Astronomy: Visions for the 21st Century* was held from 3–6 August 1994 at Penticton, B.C. The purpose of the workshop was to consider the directions of radio astronomy and international plans for new instrumentation, with a view to providing a framework for discussion of instrumental priorities for Canada's next generation radio astronomy facility. Eighty-nine scientists from Canada, and 10 other countries active in radio astronomy (Australia, France, Japan, Korea, Mexico, Netherlands, Spain, Sweden, United Kingdom and the United States) participated in the workshop. A program and list of participants is attached.

The first three and one-half days were devoted to discussions of the current role and future direction of radio astronomy in seven major areas of modern astrophysics. Invited talks from international and national experts in each field, and the open panel discussions, made it clear that radio astronomy has played and will continue to play a profound and unique role in the investigation of fundamental questions in all areas of astronomy.

> *Galaxies* – Observations of atomic hydrogen at high sensitivity and resolution will provide the means to trace the history of galaxy interactions and cluster mergers, Such observations are key to our understanding of galaxy evolution and dynamics and the hierarchy of large scale structure in the Universe. Sensitive, high resolution observations at millimetre and sub-millimetre wavelengths will trace the epoch of star formation during the early evolution of galaxies via red-shifted emission from the CO molecule and eventually the C^+ ion. Studies of

individual galaxies are also important for understanding the evolution of molecular and atomic gas and dust in environments different from those found at the present epoch in our Milky Way. Highly sensitive, spectroscopic observations of the gaseous medium will allow us to probe the internal dynamics of galaxies to faint levels, and thus sample a broader range of galaxy types and more distant cosmological epochs.

Active Galactic Nuclei – Active nuclei of galaxies are thought to contain supermassive black holes in a violent interaction with the nuclear material of the host galaxy. The highest resolution images of the central cores of active galactic nuclei have been obtained by VLBI techniques at centimetre, and recently millimetre, wavelengths. VLBI is an area where sensitivity has been a major limitation, since flux density generally decreases on the smaller spatial scales measured by large interferometer baselines. The exciting possibility of imaging galactic nuclei at the sub-parsec scale will be realized with extremely sensitive centimetre wavelength telescopes operating in concert with orbiting antennas, or a large millimetre antenna operating as part of a global network. At millimetre wavelengths, high sensitivity, high resolution observations of infrared luminous galaxies will allows us to probe the connection between nuclear starburst phenomenon and the formation of active galactic nuclei.

Cosmology – The chief contributions of radio astronomy to the field of cosmology have been measurements of the properties of the cosmic microwave background radiation (which has its peak intensity at radio wavelengths) and the study of the evolution and space distribution of discrete, cosmological radio sources. Advances in the sensitivity and stability of radio instruments promises to place fundamental constraints on dark matter models of Universe through measurements of the background anisotropy over many spatial scales. High sensitivity, high resolution studies of large samples of discrete sources will resolve some of the puzzles in our present understanding of the space and luminosity distribution of cosmological radio emitters such as quasars, and radio and starburst galaxies. Primordial galaxies will be revealed and studied by radiation at radio wavelengths from atomic lines of H, CO and C^+.

Interstellar Medium – The interstellar medium (ISM) is the substrate of the Milky Way; a complex web of physical and chemical interactions in the tenuous medium between the stars. Because of the characteristically low temperatures of the ISM, radio astronomy is the principal tool employed in its study. This will continue to be the case, and the technological advances anticipated in the next decade or so foretell an information explosion in our knowledge of the interstellar medium and of the chemistry that occurs in it. Large, mm and sub-mm wavelength arrays will provide unprecedented sensitivity and angular resolution, permitting us to exploit the chemical differentiation that characterizes phenomena such as protostar formation, circumstellar and protoplanetary discs, stellar mass loss, bipolar outflows, and extragalactic star formation. A major new area of research into the ISM involves the nature of the structure itself, and understanding of the processes and phenomena that are imbedded and reflected within that structure on all scales. The data required for fundamental breakthroughs in this area will come from instruments with high sensitivity and large spatial dynamic range at all wavelengths.

Stars – The penetrating power of radio waves and the high resolving power available through radio interferometry yield unique and powerful views of often short-lived energetic phases of stellar evolution. The range of phenomena probed include the solar system-sized, ionized and dusty environments of protostars, the violent energetics of gravitationally collapsed companions in binary star systems, the mass ejections of evolved stars as they approach their end state as either supernovae or white dwarfs, and the collapsed remnants of supernovae. Radio emission from stars is a relatively young area, that has exploded during the past decade as resolving power and sensitivity of radio telescopes have improved. Indications are that we are only scratching the surface. The promise of dramatic increases in sensitivity and resolution in future instrumentation at both cm and mm wavelengths opens up exciting new possibilities for filling gaps in the story of star formation, evolution and death, and for detecting a diversity of new phenomena.

Solar and Planetary – Fundamental understanding of relationship between surface phenomena and flaring activity on the Sun requires the ability to image the entire solar disk at high angular resolution with high intensity dynamic range and high time resolution. This capabilities does not currently exist. The penetrating power of radio photons will allow the chemical composition and dynamics of atmospheres close to planetary surfaces to be studied at high resolution with millimetre and submillimetre arrays. The mineralogy and physical properties of the surfaces of terrestrial planets and asteroids can be studied via high sensitivity studies of thermal continuum emission from centimetre to submillimetre wavelengths.

The instrumental capabilities required to make the next step in observational radio astronomy can be viewed as a multi-dimensional parameter space. The fundamental scientific questions facing the next generation of radio astronomers will be accessible through exploitation of new, unexplored areas of this parameter space. The scientific discussion at the workshop demonstrated the dimensions to this parameter space.

- sensitivity
- observing wavelength
- resolving power
- spatial dynamic range
- intensity dynamic range
- radiometric precision and stability

Although new technology allows, or holds the promise of, major advances in all these dimensions, the unexplored region of this space is too large to be sampled by a single new instrument.

Current International Situation and Prospects

Metre Wavelengths

Modern radio astronomy has largely ignored the potential of observations at wavelengths of several metres. This can be attributed to a historical thrust for higher resolving power through observations at shorter wavelengths, and the problem of the phase scattering screen of the ionosphere which has rendered high resolution, phase coherent interferometry at these long wavelengths impossible. However, recent technological advances promise to make the scattering problem tractable. Instrumentation for high resolution interferometry at metre wavelengths now appears possible and would be relatively inexpensive to construct.

Decimetre and Centimetre Wavelengths

Major astronomical facilities for observations at decimetre and centimetre wavelengths have been in place for some time. The world's most powerful connected element interferometers function at these wavelengths. These instruments have been in operation for some time and are reaching a mature state. The thrust for new instrumentation in this decade is toward higher resolving power via Very Long Baseline Interferometry techniques. Examples of this are the U.S. Very Long Baseline Array which is currently beginning operations, the European Joint Institute for VLBI with a large correlation facility under construction and the Australian Long Baseline Array. Toward the end of the decade, this technique will be extended into space with two orbiting VLBI missions, *VSOP* and *RadioAstron*.

Decimetre and centimetre wavelength radio astronomy will thus reach the extreme of resolving power that is technological feasible for the forseeable future, within this decade. The new frontier at these wavelengths is sensitivity and spatial dynamic range. Increase in sensitivity of at least an order of magnitude is required to address the fundamental scientific questions. The interferometric solution to the problem of resolving power imposes a spatial filter upon the measured sky brightness distribution. In general, the higher the resolving power the more drastic is the spatial filter. The ratio of largest to smallest baseline on todays large interferometers and VLBI arrays is about 100, allowing detection and imaging of radiation only from features having spatial scales up to a few 100 times larger than the resolution limit. Current knowledge of the interstellar medium of our Galaxy and of the structure of the universe show us that processes and phenomena occur over the tremendous range of spatial scales. One of the new frontiers at all wavelengths is high spatial dynamic range, i.e. an instrument that responds to radiation on a large, contiguous range of spatial scales.

A proposal for a next generation decimetre telescope was presented by the Dutch astronomers. This instrument, the so-called square kilometre telescope (SKT), would provide an improvement in sensitivity of two orders of magnitude over existing telescopes. As a point of comparison, at optical wavelengths, a similar factor of sensitivity improvement over present technology would be obtained by constructing an optical telescope with 40 metre diameter. The scientific impact of such a device would be phenomenal. Operating at wavelengths down to at least 21 cm (the atomic hydrogen emission line), the SKT will require resolving power better than $1''$ because of the high area density of discrete extragalactic radio sources at very low flux density levels. The Dutch concept calls for innovative use of digital technology that would allow the telescope to form many beams on the sky simultaneously. An array of antennas out to baselines of about 100 km, would provide sub-arcsecond resolution. The device would therefore be a fast, extremely sensitive device with good resolution and high spatial dynamic range.

An alternate instrumental concept for a large dm/cm telescope has been put forward by T. Legg of HIA. This concept involves a very large, long focal length (a few thousand metres) surface of panel segments laid out upon a quasi-static structure. A limited amount of reshaping of the surface would be made possible by actuators. Receivers for the dishes would be put in place via remote-controlled hovering devices,and steering would be accomplished by movement of the receivers. The concept might make possible antennas with collecting areas of order 1 square kilometre operating at wavelengths close to 1 cm at relatively low cost.

Millimetre Wavelengths

Radio Astronomy at millimetre wavelengths is in a state similar to that of dm/cm astronomy about 15 years ago. There are a several intermediate to large single dish antennas that have been operating for several years (e.g. Nobeyama, IRAM, Onsala, Kitt Peak) and four small interferometers, each with a handful of antennas, the Nobeyama Millimeter Array (NMA), the Owens Valley Millimeter Array (OVRO), the Berkeley-Illinois-Maryland Array (BIMA) and the array of the Institut de Radio Astronomie Millimétrique (IRAM) in Spain. These arrays operate predominantly at 2.6 mm. Only OVRO and IRAM operate at the shorter wavelength of 1.3 mm. Construction of a new large single-dish telescope in Mexico is planned for the end of this decade.

The existing millimetre arrays provide images of continuum and CO line emission at a resolution of about $1''$. However, the small number of antennas (typically 5 or 6) severely limits both the speed of the instruments and the dynamic range and sensitivity of the images. To address these limitations, the next major step in millimetre wavelength radio astronomy is toward large arrays of many antennas. There are three proposals in place for large millimetre arrays. If successful, these proposals would lead to construction after the year 2000. Unlike the technological developments that will be required for the next generation telescopes at dm/cm wavelengths, much of the technology required to build and operate theses arrays has been tested in development of the existing smaller millimetre arrays.

The U.S. National Radio Astronomy Observatory (NRAO) has a long-standing proposal to construct a northern-hemisphere, millimetre array of 40 antennas. This proposal is the most advanced of the three. Approval from the U.S. National Science Foundation for at least the initial design phase is expected shortly. While the larger number of antennas will yield greatly enhanced intensity dynamic range over the existing arrays, the improvement in sensitivity will be only a factor of a few. This array will operate at wavelengths of 2.6, 1.3 and 0.8 millimetres.

Japan has a more recent proposal for a large array. The Japanese Large Millimeter and Sub-millimeter Array (LMSA) would also function at sub-millimetre wavelengths. Sites for the LMSA are being explored in both the northern and southern hemispheres.

The European community is preparing a proposal for a large millimetre array in the southern hemisphere. The European concept calls for an array with about 3 times the collecting area of the NRAO proposal. Unlike the U.S. and Japanese projects, the

European project will likely involve several countries. The European array would exceed an order of magnitude improvement in sensitivity over existing millimetre arrays. Like the NRAO proposal, this array would operate at wavelengths of 2.6, 1.3 and 0.8 mm.

Sub-millimetre Wavelengths

At sub-millimetre wavelengths there are only three single dish instruments currently operating, the James Clerk Maxwell Telescope (JCMT) and the CalTech Sub-millimeter Observatory (CSO) on Mauna Kea, and Swedish ESO Sub-millimeter Telescope (SEST) in the southern hemisphere. We are at the early stages of exploitation of this wavelength regime. The step from single-dish instruments to interferometry is in the exploratory phase. Single baseline experiments, joining the JCMT and CSO have recently been carried out. Plans for the first multi-element interferometer are well advanced. The Smithsonian Astrophysical observatory will construct a 6-element sub-millimetre array on Mauna Kea, close to the JCMT site. The array is scheduled for completion in 1997.

Sub-millimetre astronomy, and interferometry in particular, is extremely challenging because the atmospheric window is almost opaque. Only the very best sites provide access to this window and measurements indicate that the interferometric observing efficiency will not be high even at those sites. For example, measurements of transparency and phase stability on Mauna Kea suggest that, in the absence of possible phase tracking techniques that are yet to be proved or developed, only about 10% of the observing time with the SAO interferometer will be of sufficient quality for sub-millimetre observations at 0.45 mm wavelength. A significantly larger fraction of the time would be suitable for observations at 0.8 mm.

The Japanese LMSA may provide the step beyond the SAO array to a large sub-millimetre array, probably sited at a very high altitude in South America.

Future Directions for Canadian Radio Astronomy

In recommending possible directions for Canadian involvement in a next generation radio astronomy facility in the first decade of the 21st century, we were guided by the following requirements.

1. The instrumentation available to the Canadian community in the 21st century should match as closely as possible the scientific aspirations and vision of the Canadian community.
2. Canada should be a significant partner in the facility (i.e. Canada should not be a minor partner in the presence of a major partner).
3. The facility should contain a significant element of Canadian scientific and intellectual property. Canadian scientists and engineers should be involved in the scientific and technical design of the facility.

Canada has a 25% share in the James Clerk Maxwell Telescope and fully owns and operates the decimetre array of the Dominion Radio Astrophysical Observatory. Canadian astronomers also make active use of foreign facilities (e.g., the Very Large Array and OVRO). With the recent commissioning of high quality sub-millimetre receivers on the JCMT, astronomers are now able to exploit well the excellent antenna and site. Over the next several years focal plane array receivers at continuum and spectral line will provide dramatic improvements to the imaging efficiency of the telescope. The DRAO is just completing a major upgrade from 4 to 7 antennas and construction of a new digital correlator system. These new capabilities increase the speed of the instrument by a factor of 4, and allow construction of very high intensity dynamic range images. Both of Canada's facilities provide instrumental capabilities that are unique world-wide, and both will enable leading research to be carried out for at least the next 10 years. Canada has a growing community of astronomers that makes use of both these instruments. In recognition of this fact and the scientific ambitions of our community, the vision for the future of Canadian radio astronomy should include access for Canadian astronomers to next generation instrumentation at both decimetre/centimetre and millimetre/sub-millimetre wavelengths.

With the above considerations, the scientific organizing committee has reviewed and examined the options for Canadian participation in a next generation radio astronomy facility. We recommend the following actions be undertaken in the near future.

- Explore the possibility of a partnership in the Smithsonian Astrophysical Observatory Sub-millimeter Array project.
- Identify a possible Canadian role in the European southern-hemisphere millimetre array proposal
- Examine the feasibility of a 1 square kilometre dm/cm telescope concept in collaboration with the proponents in Holland and elsewhere, and identify a possible Canadian role in that proposal.
- Undertake technical studies to assess the feasibility and limitations of the T. Legg large telescope concept.

At this point in time, the committee, on the whole, views these possibilities, with equal priority, as exciting steps toward the next generation of radio astronomy instrumentation.

Getting There from Here

The committee recommends that a working group be set up and chaired by the HIA Coordinator of Future Radio Telescope Initiatives. The purpose of the group will be to oversee the execution of the four recommendations, to prepare a detailed report on each and to work toward building a community concensus. We hope that the report can be produced on a time scale of about one year. Upon completion of the report, a priority ranking for the next Canadian radio telescope project should be carried out through a process endorsed by CASCA.

This is an opportune time to establish a direction for the next Canadian national radio astronomy facility. Several nations are at a similar planning stage, and it is clear that few nations can embark upon a project of the required scope alone. This is certainly the case for Canada. It is also clear that exciting instrumental and scientific visions are being forged for new radio astronomy facilities at several wavelengths. Canada has a strong, dynamic and young community of astronomers with a vision that encompasses observational radio astronomy at both dm/cm and mm/submm wavelengths. Yet it seems unlikely that Canada can hope to participate in a significant manner in more than one major radio facility. One way to reconcile these conflicting realities, is to help formulate a rational, international plan for a suite of next generation radio facilities, with the aim of providing the Canadian community with access to all wavelengths. Both the International

Astronomical Union (IAU) and the International Union of Radio Science (URSI) have formed working groups to define next generation instruments at both dm/cm and mm, and to explore cooperative modes for their realization. It is certainly in the interests of smaller countries, like Canada, to contribute to furthering this process. In sponsoring the workshop on visions for the 21st century, Canada has taken the lead in bringing diverse international interests together to discuss new directions. We should build upon this step and work with the international agencies to help to establish an international plan.

The next 10 years are crucial ones for radio astronomy in Canada. We will be forging an intellectual role for our scientists at a time when major investments in new international facilities are taking place. By the year 2000, the international vision for the next generation of instruments will be in place. Canada's current standing as a nation of excellence in both the instrumental and scientific elements of radio astronomy, positions us well to play an important part in that vision. It will be essential over the next decade that we maintain a strong commitment to our existing radio astronomy facilities at the JCMT and DRAO. These facilities provide the scientific tools for Canadian astronomers to carry out world-class research and they house the centres of Canadian instrumental expertise in interferometry, receiver technology at cm, mm and sub-mm wavelengths and the application of high-speed digital electronics to radio astronomy. These resources will be essential in our competition for a leading role in 21st century radio astronomy.

In summary, the scientific organizing committee makes the following additional recommendations to NRC with regard to the process of defining and realizing a next generation radio astronomy facility for Canada.

- Set up a working group to explore and report on the four possibilities selected by the committee.
- Participate in discussions toward formulation of an international plan for development of the next generation of radio astronomy facilities.
- Maintain commitment to our current generation of radio astronomy facilities during the transition to the next instrument.

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