

DIVISION X

RADIO ASTRONOMY

RADIOASTRONOMIE

Division X coordinates, within the structure of IAU, activities of observational and theoretical astronomers interested in phenomena that are detectable at radio wavelengths and in instrumentation for such observation.

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Division X WG

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Division X WG

Interference Mitigation

INTER-DIVISION WORKING GROUPS

Division IX-X-XI WG

Astronomy from the Moon

Division IX-X WG

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Division X-XII WG

Historical Radio Astronomy

TRIENNIAL REPORT 2009-2011

1. Introduction

This triennium has seen a phenomenal investment in development of observational radio astronomy facilities in all parts of the globe at a scale that significantly impacts the international community. This includes both major enhancements such as the transition from the VLA to the EVLA in North America, and the development of new facilities such as LOFAR, ALMA, FAST, and Square Kilometre Array precursor telescopes in Australia and South Africa. These developments are driven by advances in radio-frequency, digital and information technologies that tremendously enhance the capabilities in radio astronomy. These new developments foreshadow major scientific advances driven by radio observations in the next triennium. We highlight these facility developments in section 3 of this report. A selection of science highlight from this triennium are summarized in section 2.

This report also includes updates from Division X working groups on Astrophysically Important Spectral Lines, and on Interference Mitigation. Both are areas of growing importance as instantaneous bandwidths, sensitivities and the coverage of the electromagnetic spectrum at radio wavelengths increase with the advance of new technologies. A report from the WG on Astronomy from the Moon is also included. Ultra low frequency radio astronomy promises to be one of the first astronomical uses of the lunar platform.

The former DX Working Group on Global VLBI was terminated during this triennium. This working group was formed during the early days of the expansion of VLBI to global baselines, and provided a forum for coordination of programs and standardization of data and technologies from diverse regions of the globe. Intercontinental VLBI is now well served by dedicated arrays, correlation facilities and programs that are managed by national and international agencies. We take this opportunity to thank the members of the GVWG who have played a strong role in the successful development of this discipline as a global enterprise.

2. Science Highlights

2.1. Pulsars

Efforts to detect a stochastic gravitational wave background via high precision pulsar timing observations continue world-wide. The latest results have been reported two groups, one combining the Parkes radio telescope and Arecibo Observatory data, the other combining data from various European radio telescopes. Upper limits continue to improve—steadily approaching the level expected from the ensemble population of supermassive black hole binaries expected from mergers of galaxies—helped by a combination of improved understanding of instrumental effects and new analysis techniques of the data (Yardley *et al.* 2011; van Haasteren *et al.* 2011).

In conjunction with NASA's Fermi Gamma-ray Space Telescope, a world-wide network of radio telescopes has been observing un-identified Fermi sources for pulsars. The result has been a dramatic increase in the number of millisecond pulsars, with radio observations of Fermi sources likely to discover many more millisecond pulsars than were discovered since the original discovery of millisecond pulsars (Abdo, Ackermann & Ajello 2010).

Analysis of a pulsar survey with the Parkes radio telescope has revealed a millisecond pulsar with an extremely unusual companion. The companion's mass is comparable to that of Jupiter but its density suggests that it is an ultralow-mass carbon white dwarf. Such a system may help reveal how millisecond pulsars are produced as well as elucidate various binary evolution channels. (Bailes, *et al.* 2011).

A new mass determination for PSG J1614-2230 makes it the most massive pulsar known and rules out a number of equations of state for nuclear matter, including many exotic hyperon, kaon models. The derived companion mass is $0.500 \pm 0.006 M_{\odot}$, and the pulsar mass is $1.97 \pm 0.04 M_{\odot}$ (Demorest *et al.* 2010).

2.2. Galaxies

The Arecibo Legacy Fast ALFA Survey (ALFALFA) continued with its blind search of the Arecibo sky for neutral hydrogen 21 cm emission. When complete, ALFALFA will begin to approach the volumes needed for a representative cosmological survey. Currently, the ALFALFA survey is 40% completed and already is yielding significant improvements in the source density compared to previous HI surveys. Already it is clear that there are few gas-rich, optically dark systems in the local Universe (Haynes *et al.* 2011)

A variety of instruments, including the Very Large Array (VLA) and EVLA, Multi-Element Radio-Linked Interferometer Network (MERLIN), and the European Very Long

Baseline Network (EVN), have been used to probe sub-millimeter galaxies (SMGs) to assess the relative contributions between accretion onto supermassive black holes and star formation in producing their luminosity (e.g. Briggs *et al.* 2011),

A suite of radio instruments is being used to probe the innermost regions of active galactic nuclei (AGN) where the most energetic processes happen. The observations are being conducted in coordination with NASA's Fermi Gamma-ray Space Telescope and include a world-wide network of both single-dish and imaging instruments in both hemispheres.

Observations of the CO line over cosmological time scales are beginning to illustrate how galaxies turn their gas into stars. In particular, existing instrumentation is beginning to illuminate processes at redshifts larger than 1, when the star formation rate density of the Universe reached its peak. (e.g. Genzel *et al.* 2010). CO emission has been detected from the most distant known submm galaxy at $z=5.3$. These observations show the cold gas that fuels the star formation, implying extreme amounts ($> 10^{10} M_{\odot}$) of dense gas in this forming elliptical galaxy. (Riechers *et al.* 2010)

2.3. Galaxy Clusters

A bright, giant radio halo was detected in MACS J0717.5+3745; the most distant cluster currently known to host a radio halo. This radio halo is also the most powerful ever observed, and the second case for which polarized radio emission has been detected, indicating that the magnetic field is ordered on Mpc scales (Bonafede *et al.* 2009).

It has been confirmed that the radio spectra of halos are related to the cluster temperature, being flatter in hotter clusters (Giovannini *et al.* 2009). Since the cluster temperature is a good indication of the turbulence present in the ICM, this correlation favours the interpretation that turbulence is the mechanism responsible for supplying energy to relativistic electrons.

The correlation between cluster X-ray luminosity and radio power confirms the dichotomy between merging clusters and relaxed clusters. Models of diffusive shock acceleration suggest that in shocks that occur during cluster mergers, particles are accelerated to relativistic energies. In the presence of magnetic fields, these particles emit synchrotron radiation and may form radio relics (van Weeren *et al.* 2010). The new detections of many radio relics that display highly aligned magnetic fields, a strong spectral index gradient, and a narrow relic width, confirm this model and give measures of the magnetic field in a previously unexplored site of the universe.

2.4. Active Galactic Nuclei

In 2009 for the first time e-VLBI science observations were carried out with a global array, reaching a maximum baseline length of 12,458 km, including telescopes in Europe, East Asia, and Australia. The γ -ray narrow line Seyfert 1 PMN J0948+0022 observed at 22 GHz, showed a structure dominated by a bright component, more compact than 55 μ arcsec, with a fainter component (Giroletti *et al.* 2011). Relativistic beaming is required by the observed brightness temperature. The results show that global e-VLBI is a reliable and promising technique for future studies.

M87 was observed at six frequencies with VLBA, allowing a positional accuracy of the location of the central black hole relative to the jet base (radio core) of about 20 μ arcsec (Hada *et al.* 2011). As the jet base becomes more transparent at higher frequencies, the multifrequency position measurements of the radio core enable a determination of the upstream end of the jet. The data reveal that the central engine of M87 is located within 14-23 R_s of the radio core.

3. International Radio Astronomy Facilities Development

The *Atacama Large Millimetre Array* (ALMA), which is a partnership involving institutes in Europe, North America and East Asia, in cooperation with the Republic of Chile, is making rapid progress towards its goal of providing dramatic improvements in sensitivity and resolution for astronomy at millimeter and sub-millimeter wavelengths. The initial commissioning results have confirmed that the accuracy, sensitivity and stability of the key components are close to the ambitious goals set for them. The tests have also demonstrated that all parts of the system can be made to work together to produce high-quality images. A series of observations have been made for the Scientific Verification program - aimed at producing data that can be compared directly with observations made with other (sub-)millimeter arrays - and the results are being released publicly as they become available. The first call for proposals ("Cycle 0") was sent out in March 2011 and scheduled observations with 16 antennas, 4 receiver bands and baselines of up to 400m started on 30th Sept.

As of November 2011, 24 antennas were in operation. A further eight antennas, with full complements of receivers, are being tested. The antennas in operation include examples of all three of the 12m designs, as well as four of the 7-m diameter antennas for the ALMA Compact Array. Final versions of the local oscillator system, the correlators and all the other electronics and control and monitor systems are in place, and the infrastructure (roads, power and communications) is expected to be completed early in 2012. ALMA's capabilities will continue to grow during 2012 and there will be further calls for proposals from the user community. It remains the target to have the full system with sixty-six antennas and baselines of up to 16km in operation during 2013.

The *Expanded Very Large Array* construction project continues to proceed on schedule for delivery by December, 2012. Implementation of all major systems is complete or approaching completion, and the new instrument is well into standard operations. Remaining tasks include the completion of Front End receiver hardware, the installation of the 4 Gs/s 3-bit samplers, and the implementation of specific software support. Antennas continue to be outfitted with new wide band receivers. Well over half of these are now in service. The schedule to deploy these remaining receiver bands has held steady for the past two years. The retrofit of existing Data Transmitter modules with wideband samplers has begun with the installation of the first twelve. The 3-bit samplers, required for the full 8-GHz operation of the EVLA, are scheduled to be fully deployed by September, 2012. Observing capability with 2 GHz bandwidth is complete, monitor and control of antenna electronics is fully realized, and 3-bit operation is supported by the correlator and EVLA. Notable work which remains includes providing support for sub arrays and data pipeline processing.

LOFAR is a low-frequency radio interferometer nearing completion in Europe. The antenna array consists of two distinct antenna types: the Low Band Antenna (LBA) operates between 10 and 90 MHz and the High Band Antenna (HBA) between 110 and 250 MHz. Within the Netherlands 33 stations are currently online and are distributed over an area about one hundred kilometres in diameter in the North-East of the Netherlands. The remaining seven stations in the Netherlands are expected to be completed in early 2012. Eight international stations are completed in Germany (5), Sweden (1), the UK (1) and France (1). The array is currently undergoing intensive commissioning with an initial all-sky calibration survey underway. In addition to the station roll-out, the final deployment of computing hardware at the LOFAR central processing facility is complete and development of the science processing pipelines is making steady progress. An initial

release of the full system is slated for beginning of 2012. These capabilities will be offered to the community as part of an initial Announcement of Opportunity in early 2012.

At the *Westerbork Synthesis Radio Telescope* a Square Kilometre Array pathfinder project, APERTIF, aims to increase survey speed by installing phase-array feed systems operating at 1.4 GHz. The project successfully passed its detailed design phase and is expected to roll out in 2013. ASTRON has started the process that will define the science to be done with APERTIF. Most of the observing time with APERTIF will be devoted to large surveys, the data products of which will be made available to the entire community through an open-access archive. A call for expressions of interest for APERTIF was issued in July 2010. The response was very large, and efforts are underway to combine the proposed surveys into a coordinated campaign of duration about five years.

The *Giant Meter Wave Telescope* is undergoing a major upgrade whose main aims are to provide seamless frequency coverage from 50 to 1450 MHz, improved sensitivity with better feed and receivers, increase instantaneous bandwidth to 400 MHz, and improve computing and infrastructure facilities. As part of these developments, a series of significant upgrades have been completed during 2009-11, notable amongst which are completion and release of a 32 MHz software backend for correlation, beam forming and pulsar processing, development of a wide-band optical fibre link, and development of automated software systems for scheduling, data archiving and retrieval.

The *Five-hundred-meter Aperture Spherical Telescope* (FAST) will be the world's largest single dish sited in a karst depressions called Dawodang in south Guizhou province in China. Its active 500-metre diameter reflector directly corrects for spherical aberration. The light-weight focus cabin is driven by steel cables and has a robotic secondary system to precisely position the receivers. Working at frequency range of 70MHz - 3 GHz, the telescope will provide a powerful tool for HI surveys, pulsar science, radio spectra and international VLBI. The report on starting of construction was approved by the Chinese government in March 2011 and early science is expected to start in 2016.

The *Sardinia Radio Telescope* is a 64-m dish which is being completed in the Sardinia Island (south Italy) and will be used as a single dish, for VLBI, and for satellite tracking. It will be the second largest dish in Europe, and the largest one with an active surface; the primary mirror is made of a mosaic of more than 1000 actuated adjustable panels. It will represent a major addition to the European VLBI Network and will be used for space VLBI observations in conjunction with the *RadioAstron* antenna. First light receivers are in the range 0.3 - 22 GHz. The high frequency receiver is a 7-horns array, supplying a larger field of view and high imaging speed. Early science is expected in 2012.

The *RadioAstron* space radio telescope was launched from Baikonur on July 18, 2011, and its 10-meter antenna was successfully unfolded on July 23. Since then, the telescope has been undergoing in-orbit checkout. In particular, the on-board hydrogen maser has been switched on and is working properly; the radiometers have been turned on and the system temperature in all four bands (P, L, C, and K) has been found to be close to the specifications. First light from Cassiopeia A was detected at 92 and 18 cm and the effective areas are close to the expected values. Fringe searches are expected to start on November 15 2011 and the Early Science Program at the beginning of 2012.

The *Square Kilometre Array* (SKA) will be the next-generation global radio telescope operating from metre to centimetre wavelengths. The early stage planning and design of the SKA has been undertaken as a collaboration of institutes from over 20 countries. A crucial steps for the SKA project were taken in the last week of March 2011. A Founding Board was created with the aim of establishing a legal entity for the project by end of 2011, and agreeing the resourcing of the pre-construction phase from 2012 to 2015. Nine countries signed the initial agreement, and a number of additional countries are expected

to join the Board upon establishment of the SKA legal entity. At its first meeting on 2 April, the Founding Board decided that the location of the SKA Project Office during the pre-construction phase will be at the Jodrell Bank Observatory in the UK.

The SKA System Conceptual Design Review was passed in February 2011. Several of the SKA sub-system CoDRs (signal processing, aperture arrays, antenna) have now also passed review and all reviews are scheduled for completion by January 2012. The overall system will reach Preliminary Design Review stage at the end of 2012; construction is currently planned to commence in 2016.

The site characterization for the SKA location is well advanced. Information and reports from both of the candidate sites in Australia/New Zealand and southern Africa are under review. The decision on the SKA site is expected in early 2012. SKA precursor telescopes that demonstrate technologies under development for the SKA are under construction on both proposed sites.

The *Australian Square Kilometre Array Pathfinder* (ASKAP) telescope is a wide-field (30 sq deg) radio survey telescope currently being constructed at the Murchison Radioastronomy Observatory in Mid-West region of Western Australia. The telescope will comprise 36 12m-diameter antennas equipped with 192-element phase array feeds providing up to 30 simultaneous observing beams. The telescope will be operational over the range 0.7-1.8 GHz and a maximum angular resolution of 10 arcsec. It will have processed bandwidth of 300M Hz over 16K channels. As of October 2011, 10 antennas have been constructed, will all 36 to be built on site by March 2011. The first six antennas are expected to be conducting science observations with the phased array feed system by mid-2012. The wide field-of-view provided by the focal plane array receiver systems optimizes ASKAP for rapid imaging surveys. Ten large Survey Science Projects have been awarded survey status; comprising 350 scientists from over 150 institutions internationally. ASKAP operates an open access model, and all data will be available to the international community with no proprietary period.

The *MeerKAT* array, being constructed on the South African SKA candidate site in the remote and arid Karoo region, will consist of 64 Gregorian offset 13.5-m antennas. The array will initially extend out to 8 km baselines. MeerKAT is a precursor for the mid-frequency dish component of the SKA. Novel reflector manufacturing techniques are being prototyped to ensure good performance across the operating bandwidth at an affordable cost for both MeerKAT and the SKA. The antennas will be equipped with a suite of cryogenically cooled single-pixel receivers covering a frequency range of 580 MHz to 15 GHz. The radio frequency outputs from the receivers will be digitized directly to ensure signal fidelity, and the array signal processor will be based on FPGA processors (developed as part of the CASPER collaboration) and commodity computing elements (such as GPUs and other multi-core devices). MeerKAT will be the most sensitive centimetre wavelength instrument in the southern hemisphere and will be completed in 2016. Ten large-scale science surveys involving more than 500 scientists have been allocated 70% of the initial observing time on the MeerKAT, amounting to five years in total. A seven-antenna prototype array, named KAT-7, has been constructed on the Karoo site, and is currently conducting commissioning science observations.

4. WG Reports

4.1. *Astronomy from the Moon - chair: Heino Falke*

The European Space Agency (ESA) plans its first lunar lander in the region of lunar south pole in 2018. A primary goal is to demonstrate a soft precision landing.

Scientifically the following topics are being studied by ESA as part of the mission:

(a) Investigating the lunar conditions (dust, plasma, ionosphere, availability of natural resources) in preparation for human settlements on the moon.

(b) Performing Moon-based Ultra-Long-Wavelength Astronomy (ULWA). Using a single radio antenna covering kHz-100 MHz a variety of scientific issues can be addressed, including measurement of Solar bursts and radio emissions from the planets, the global signal of the Epoch of Reionization of the universe (Jester & Falcke, 2009), and emission of ultra high-energy cosmic rays and neutrinos from the moon regolith (Scholten 2010).

A Dutch-Chinese collaboration has funded a joint PhD study aiming at engineering of Moon-based instrumentation for ULWA. An Indian - Russian collaboration is considering an ULWA experiment in the framework of the joint Moon exploration program with possible implementation after 2018. Using the results of UK-SE FIRST and ESA-NL DARIS studies, a concept of a free-flying ULWA mission SURO (a low-cost array of 9 satellites near L2) was proposed for a cosmic vision call. Although the proposal did not succeed, new submissions are planned.

In the US NASA's Lunar Science Institute has been very active with various projects.

- Dark Ages Radio Explorer. A concept for a lunar-orbiting spacecraft carrying a dipole antenna for the purposes of making measurements of the global highly-red shifted 21-cm signal from the end of the Dark Ages and Cosmic Dawn. A proposal was submitted to the NASA Explorer program. While it received favorable reviews, it was not funded.

- Technology development for a future lunar radio array based on polyimide film. An antenna mated to a commercial off-the-shelf receiver has been fielded. Absorption due to the terrestrial ionosphere was detected, though the original target was a diurnal variation in power due to the Galactic background, which was not achieved. The test results are being assessed.

- Technology development for the deployment of the antennas of a future lunar radio array using a spring-loaded anchor system. Initial tests of a proof-of-concept system have been conducted, and more detailed engineering designs are being developed.

4.2. *Astrophysically Important Spectral Lines - chair: Masatoshi Ohishi*

The frequency range, 275 -1000 GHz, is used for radio astronomy observations of important spectral lines and continuum bands. New receiver technology and new instruments (both ground-based and space based) being used in the 275 - 1000 GHz region are helping to refine the results of radio astronomy observations in this spectrum range, while similar developments in the 1000-3000 GHz range are leading to a better understanding of specific spectral lines and atmospheric windows that are of interest to radio astronomers. Significant infrastructure investments are being made under international collaboration for the use of these bands between 275 and 3000 GHz.

Frequency allocations for the use of this frequency range are not available, but the radio astronomy community is requested to identify a list of specific bands of interest between 275 and 3000 GHz towards World Radio Communication Conference 2012 (WRC2012) held by the International Telecommunication Union. A new ITU-R Recommendation RA.1860 (Preferred frequency bands for radio astronomical measurements in the range 1-3 THz) was published on February 2010, by including a list of astrophysically most important spectral lines in the frequency range between 275 and 3000 GHz that was established by the IAU Working Group on Important Spectral Lines.

Proposals for WRC2012 are being submitted (as of the end of October 2011) by governments and regional telecommunication bodies, all of which are identical and incorporate the outcome of this Working Group. To the best of our knowledge, there have been no objections to provide science communities with better electromagnetic environment. It

is thus expected that the importance of radio astronomical observations in the frequency range between 275 and 3000 GHz will be better recognized after February 2012.

4.3. *Interference Mitigation - chair: Willem Baan*

The issue of RFI Mitigation has gained more visibility within the radio astronomy community in recent years. On one side, the computing capabilities available at observatories have been augmented dramatically, while on the other side the presence of RFI has become more damaging because of changing observing capabilities. The vulnerability of radio astronomy observing systems to RFI has increased because of routinely lower system temperatures and steadily increasing observing bandwidths. Observing bandwidths now routinely cover large chunks of frequency space outside bands allocated to the Radio Astronomy Service (RAS), including bands allocated to other communication services for transmissions.

The use of these large observing bandwidths also creates the urgent need of mitigating the signals in bands outside those allocated to the RAS. Mitigation techniques implemented in new (and existing) observing systems remove the effects of RFI using automated implementations of the familiar (time-consuming) data flagging procedures. As long as the percentages data loss is small, such applications will be adequate. However, when data loss becomes significant, other techniques are needed that subtract the RFI component from the data and leave the astronomical data mostly intact. Certain forms of waveform estimation and higher-order statistics can do this but are computationally complicated and difficult to implement. RFI mitigation techniques are being introduced in modern telescopes, such as LOFAR, WMA, EVLA, eMERLIN, GMRT, and others.

The third in a series of RFI Mitigation workshop was held in Groningen, The Netherlands on 29-31 March 2010, where the most recent achievements in algorithms and implementations were presented. The presentations of this meeting can be found at <http://www.astron.nl/rfi>. All papers are available in e-literature.

Working Party 7D on Radio Astronomy of the Radiocommunication Sector of the International Telecommunication Union is preparing a Report on RFI Mitigation techniques.

A. Russell Taylor
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