New Radio Astronomy with Focal-Plane Arrays

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Abstract

By using focal-plane array (FPA) technology, the field-of-view of current cm-wave radio astronomical interferometers can be enlarged by more than an order of magnitude. FPAs are also one of the technologies under consideration for the Square-Kilometer Array (SKA). Such larger field-of-views will enable entirely new types of astronomical research and FPAs promise to have a major impact on astronomy, even well before SKA becomes operational. I discuss some of these new science applications, as well as FPA systems currently being developed, such as the APERTIF system for the Westerbork Synthesis Radio Telescope and the ASKAP in Australia.

1. Introduction

Radio astronomy is an important branch of astronomy. It has given fundamental contributions to science among which are the discovery of pulsars, the detection of the cosmological microwave background, the physics of super-massive black holes in active galactic nuclei, and the properties of dark matter in the Universe through detailed studies of the kinematics and structure of galaxies using measurements of the 21-cm spectral line emitted by neutral hydrogen. The success of radio astronomy has not only been driven by clever astronomers, but, as in all branches of observational astronomy, has also depended crucially on advances in technology. In order to maintain radio astronomy as a vibrant science that contributes to astronomy with many exciting discoveries, new and emerging technologies should continuously be applied to the instruments. There is always a need for bigger and better. This is the basic philosophy behind the plans to construct the Square Kilometer Array (SKA), a radio telescope that will surpass all existing telescopes in performance by two orders of magnitude in basically every performance indicator.

Unfortunately, building SKA is a large undertaking, it requires a global effort and a large budget to match this. Therefore, timescales are long: full SKA is not expected to be operational before 2020. However, thinking about SKA and how it could be built, has already delivered new and interesting technologies which don’t have to wait to be utilised with SKA but which can be applied now. One of these technologies is focal-plane arrays (FPA). By replacing the “single-pixel detector” that current radio interferometers employ in their focal plane by an array of detectors, the field-of-view can be enlarged by more than an order of magnitude. Although this will not improve the sensitivity, it will greatly increase the survey speed, i.e. the speed with which a large region of the sky can be observed down to a certain sensitivity. Because of this, very deep all-sky surveys can be done that previously were not conceivable. It offers a major new opportunity, namely to image the entire sky at high spatial resolution with high sensitivity and out to large distances. This will allow astronomers to embark on all kinds of new projects that, hopefully, will deliver all kinds of new and interesting science. Below I summarise a few of such projects and the science that could be done, admittedly biased by my own expertise. However, before I do this, I want to make one small remark, namely that it is interesting and useful to think about the science to be done, but one should not get blinded by it and not let it constrain the design of future telescopes entirely. No existing, or past, large astronomical observational facility is, or will be, remembered for the science that was laid out in the “science plans” that were written when these facilities were built. The most exciting science is always in the unexpected. Undoubtedly this will also be true for radio telescopes fitted with FPAs. It will be even more exciting than we now think it will be!

2. Planned FPA radio telescopes

There are two large radio astronomical facilities planned that will use FPA systems and that will operate around 1400 MHz. ASTRON in The Netherlands is planning, with a system called APERTIF, to replace the current single-pixel receivers of the Westerbork Synthesis Radio Telescope (WSRT) with a 64-element dual-polarisation FPA. With this FPA system 25 beams will be formed on the sky and hence increase the field-of-view of the WSRT by this factor. In Australia, the ATNF is constructing the Australia SKA Pathfinder (ASKAP), a new telescope to be situated in an isolated region in Western Australia. The current design of ASKAP involves 45 dishes of 12-m diameter, each dish having an FPA receiver forming 30 beams on the sky. The field-of-view ASKAP will be 30 square degrees, about a
factor 100 larger than the current radio interferometers that operate at 1400 MHz, while their sensitivity will be the same as current interferometers. The survey speed of APERTIF is 30 times that of the WSRT while that of ASKAP is even 80 times larger. Clearly, these new instruments are a major step forward in observational capabilities.

3. Neutral hydrogen studies

Hydrogen is the most abundant element in the Universe. Hydrogen gas is the major constituent of the interstellar medium, it is the raw material that stars form from. Galaxies look quite different in HI compared to how they look in e.g. the optical therefore HI studies provide important new information. Moreover, because neutral hydrogen (HI) emits the narrow 21-cm emission line, the kinematics of the HI in galaxies can also be determined by detecting Doppler shifts. For these reasons, HI studies of galaxies are very important and it is impossible to understand the formation and evolution of galaxies without knowing about the neutral hydrogen in and around galaxies. It is for this reason that the first time a telescope concept like SKA is mentioned in the literature, it is called *The Hydrogen Array*[1].

![Figure 1: Expected redshift distribution of HI detection in a medium-deep survey performed with APERTIF, compared with the redshift distribution of the galaxies in DR5 of the Sloan Survey for which spectroscopy is available. For ASKAP the distribution is basically the same](image)

The virtue of systems like APERTIF or ASKAP lies in the fact that they can cover large regions on the sky in one observation, not in their sensitivity. The redshift distribution of HI detections in an APERTIF observation of medium depth (120 hr integration) is shown in Fig.1. The peak lies around a redshift of 0.1 (30000 km/s). It will require very long integrations to detect a meaningful number of galaxies above redshift of 0.2 (60000 km/s). It is slightly depressing to note that with SKA it will take only a few minutes to detect a galaxy in HI at redshift 0.2. Because of the large field-of-view, despite the longish integration times, large samples of HI detections can be created. Depending somewhat on survey strategy, a survey of a few years with APERTIF or ASKAP will result in more than 10^6 detections. The current state of HI surveys are HIPASS[2], done with the Parkes telescope, and ALFALFA[3] done with the Arecibo dish. Taking all current surveys and other observations together, the HI information of slightly more than 10^4 galaxies is currently known, so the jump to 10^6 galaxies is enormous. Moreover, since HIPASS and ALFALFA are single-dish surveys, the low spatial resolution of those data means that the HI information is limited to global information only. With APERTIF and ASKAP, the spatial resolution will improve from several arcminutes to 10-15 arcseconds. So, instead of having only global information, we will have images of the HI and its kinematics. This will allow much more detailed studies. Finally, currently only a handful HI detections with redshift above 0.1 exist. After the FPA surveys, most galaxies detected are at these large distances.

It is clear that the amount information available on the HI in galaxies will increase dramatically, and, because of the larger distances of the detections, for the first time we will also be able to address cosmic evolution of neutral hydrogen
in galaxies. One important question in current astronomy is why the cosmic rate which stars form is declining with time. Figure 2 shows a plot of the star formation rate per unit volume as function of redshift, or, equivalently, with lookback time. This figure shows that since redshifts of a few tenths, corresponding to the Universe of about 5 Gyr ago, the cosmic star formation rate has dropped almost an order of magnitude. It is not clear why this is happening. Because star form from gas, in order to understand this drop in star formation, one will have to know about the gas at these redshifts. An interesting aspect of these HI surveys is that they will also detect, at the same time, the continuum emission from the galaxies detected in HI. This continuum emission is produced either by relativistic electrons moving though magnetic fields (synchrotron emission) or it is thermal emission of clouds of ionised gas. In both cases, this continuum emission is directly or indirectly related to the star formation rate. Therefore, the surveys will have the interesting combination that they tell us about the amount of fuel available for star formation as well as how much of that fuel is actually used, out to the relevant distances.

Figure 2: The evolution of the cosmic star formation rate from the early Universe to the present (taken from [4]) showing the large decrease in star formation in the Universe in the last few Gyr ($z$~0.5)

4. Pulsar studies

Another example of exciting science that can be done with FPA radio telescopes is searches for large number of pulsars. Pulsars are stars in the final stages of their life and they emit very regular pulses of radio emission with periods of a few milliseconds to a few seconds. They are extreme objects, of extreme density (their mass is roughly that of the sun but their diameter is only 10-20 km!!!!) and with extreme magnetic fields ($10^{12}$-$10^{13}$ Gauss). With FPA radio telescopes, it is possible to make a census of the Galactic pulsar population. There are many reasons for undertaking such a project. The first is that the larger the number of pulsar known, the more likely it is to find the rare objects. Such rare objects have proven to be excellent laboratories for all kinds of interesting physics. These objects include; binary pulsars with black-hole companions that can provide strong field tests of gravity; binary pulsars with periods of a few hours or less that can be used for tests of relativistic gravity; milli-second pulsars (MSPs) that can be used as detectors of cosmological gravitational waves; MSPs spinning faster than 1.5 ms, that probe the equation-of-state under extreme conditions; hyper-velocity pulsars with translational speeds of 1000 km/s, which probe both core-collapse physics and the gravitational potential of the Galaxy; and objects with unusual spin properties such as discontinuities (“glitches”) and apparent precessional motions. Another reason to embark on a Galactic census of pulsars is that with a large sample of pulsars, one can delineate the advanced stages of stellar evolution that lead to supernovae and compact objects. Finally, pulsar signals can be used as a 3-D probe of the interstellar medium. Measurable propagation effects include dispersion, scattering, Faraday rotation and HI absorption which provide line-of-sight integrals of the free-electron-density, the fluctuations in the electron density, the magnetic field and the neutral hydrogen density. The
determination of these observables for a large number of independent sight-lines makes it possible to construct a complete 3-D volumetric map of the Galaxy.

Figure 3 shows the detection limits of APERTIF for pulsars in the Galaxy. Basically all pulsars within 10 kpc can in principle be detected while a large fraction of the more distant pulsars will also be seen. The large field-of-view of FPA telescope makes it possible to actually survey the entire sky for pulsars to these sensitivity limits so there is enormous potential for very interesting pulsar work with such telescopes.

Figure 3. The detectability of pulsars with the APERTIF system (centre) is illustrated with the luminosity – period scatter diagram (adapted from [5]). The horizontal lines correspond to 10σ detection limits with APERTIF for pulsar distances of 10 kpc (lower line) and 100 kpc (upper line).

5. Other science

A lot of other very interesting new science can be done with FPA radio telescopes. Because it will be possible to survey the entire sky with high sensitivity and at high spatial resolution, the Faraday rotation of the polarisation plane of the radiation due to the intervening magneto-ionic medium can be determined in the direction of 10⁴ pulsars and about 10⁶ extragalactic background sources. With this information the delineation of the entire Galactic magnetic field can be determined with high spatial resolution.

Another very promising application of FPA radio telescopes is to search for transient emission – bursts, flares and pulses on time-scales up to about a month. Such emission marks compact sources or the locations of explosive or dynamic events. As such, radio transient sources offer insight into a variety of fundamental physical and astrophysical questions including the mechanism of efficient particle acceleration, possible physics beyond the Standard Model, the nature of strong field gravity, the cosmological star formation history and detecting and probing intervening media. This is perhaps the largest new observational parameter space that is opened up by FPA radio telescopes and many new surprising discoveries will be made. It might well be that it is in this area that FPA radio telescopes will make the most significant new contributions to astronomy.

6. References