Galaxies and Their Constituents at the Highest Angular Resolutions
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Prospects for High Angular Resolution at Metre to Centimetre Wavelengths

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Abstract.
The past ten years has seen very significant advances in high resolution imaging arising from the construction and routine operation of Very Long Baseline Interferometer arrays in the US, Europe and Australia. Coupled with the launch of the first VLBI antennas into earth orbit, angular resolution below a milliarcsecond has been achieved on a large number of compact objects. Nevertheless, while the application of phase referencing to VLBI observations has increased the number of sources that can be imaged by VLBI, the astrophysical impact of interferometry on baselines greater than a few tens of km, has been severely limited by sensitivity. The next decade promises to bring about very significant increases in continuum sensitivity at high angular resolution through new developments in VLBI recording devices to achieve recording bandwidths of 4 to 8 Gbits per second, and by direct optical fibre-linked long baseline arrays. In the following decade, the Square Kilometre Array will herald a new era of high resolution radio astronomy with a factor of 100 sensitivity increase. In addition to vastly increasing the sample of non-thermal sources accessible to VLBI, the SKA will open up high angular resolution imaging to a new regime of astrophysics, by enabling milliarcsecond resolution imaging of thermal radio emission. At wavelengths of a few centimetres the SKA, in combination with next generation space VLBI missions, will allow direct imaging of the x-ray emitting accretion disks in galactic nuclei.

1. Introduction

Radiation at metre to centimetre wavelengths is a crucial probe of the constituents of galaxies. Below a few centimetres wavelength the integrated radiation from galaxies is dominated by synchrotron radiation, and measures the reservoir of relativistic particles in galactic disks produced by massive star formation over some time interval that depends on the rate of energy loss from the galaxy. Intense continuum and line radiation from the nuclei of galaxies probes the structure and kinematics of black hole environments. Observations of the atomic hydrogen line at $\lambda 21$ cm measure the mass distributions of galaxies and their dark matter halos, and the physical state of their interstellar media. At centimetre wavelengths, radiation from ionized gas measures the ionizing pho-

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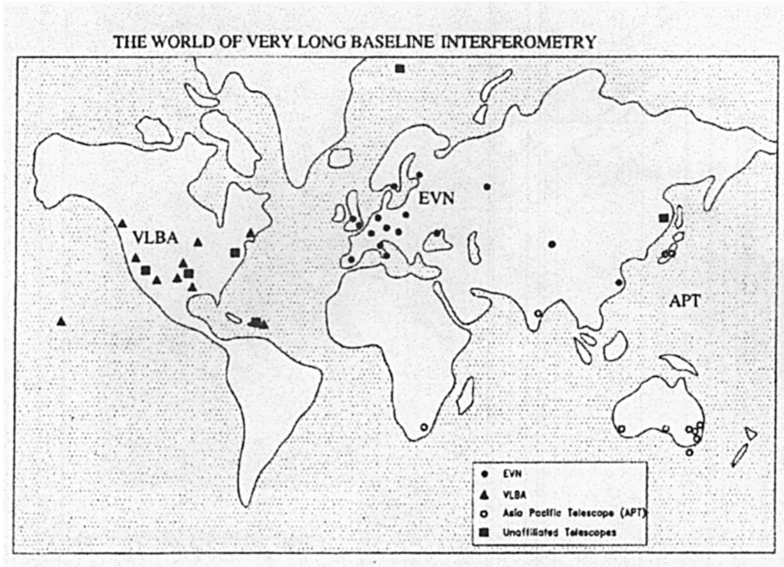

Figure 1. Joint scheduling of the three major VLBI networks in Europe, North America and Asia-Pacific now routinely allow for Global VLBI observations of very bright radio sources.

ton luminosity of galaxies and probes the environments of current massive star formation independent of dust extinction. In our own Galaxy centimetre wavelength radiation provides unique views of stars and circumstellar environments in virtually all stages of stellar evolution.

Imaging at resolution well below an arcsecond has been made possible over the last few decades by long-baseline radio interferometer arrays. However, despite the power of radio observations, only a small subset of these astrophysical phenomena can be observed at milli-arcsecond scales. The limitation is the brightness sensitivity of sparse interferometer arrays.

2. Current Status of Radio Interferometer Arrays

At wavelengths longer than ~10 cm, sub-arcsecond imaging requires baselines of order 100 km and greater These baselines are obtained using Very Long Baseline Interferometry and the radio-linked, MERLIN array. The 1990's saw a golden age of expansion for VLBI, with the commissioning of the National Radio Astronomy Observatory, Very Long Baseline Array (VLBA), the organization of the Joint Institute for VLBI in Europe (JIVE), and the Asia-Pacific Telescope. The first space radio telescope for VLBI, *HALCA*, was launched by ISAS in 1997. The cooperative international infrastructure established to provide global ground telescope support for the *HALCA* mission has lead to routine observations with Global arrays of radio telescope (Figure 1). Such observations yield high-quality, milliarcsecond resolution images of the most intense, synchrotron radio sources.

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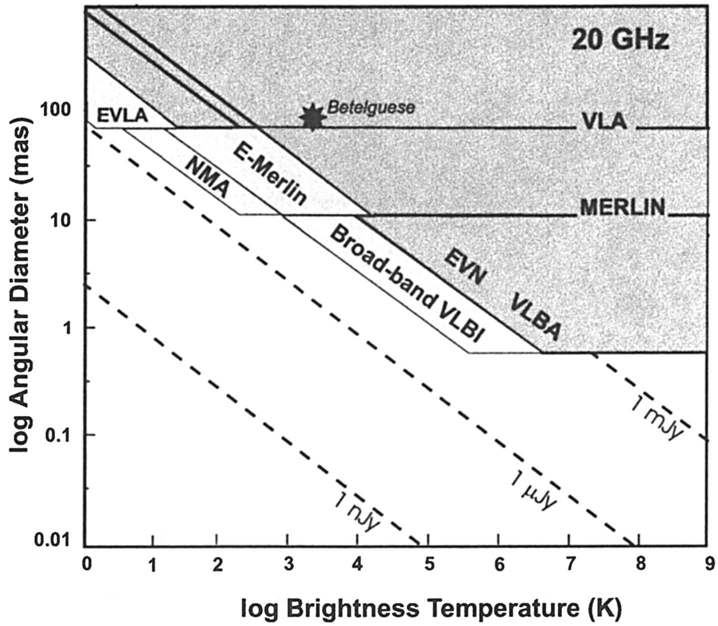

Figure 2. Brightness temperature angular size parameter space for current radio telescope arrays (gray area) and projects planned within this decade (enhanced VLA, enhanced MERLIN, the New Mexico Array and broad-band VLBI).

At wavelengths of a few cm, the largest connected element arrays achieve sub-arcsecond resolution. The Very Large Array has sufficient sensitivity to detect radiation from the thermal Bremmstrahlung sources such as compact HII regions and stellar photospheres at $\sim 0.1''$ resolution at $\lambda 1.5$cm. With approximately 10 times larger baselines, MERLIN achieves $\sim 0.01''$ resolution, albeit with much reduces brightness sensitivity, sufficient to detect only the very brightest thermal sources.

The parameter space of continuum brightness temperature and angular resolution afforded by current interferometer arrays is illustrated in Figure 2. Lines of constant source flux density appear as diagonals in this plot. The three dashed lines show the angular diameter of a source required to produce flux densities at of 1 mJy, 1 μJy and 1 nJy, as a function of the brightness temperature of the source. The region of (T_b, θ) accessible to a particular telescope array is constrained by a bottom horizontal line showing maximum resolution (baseline) and a diagonal line corresponding to the minimum detectable flux density. A radio source with a given angular radius and brightness temperature must lie above both lines to be resolved by the array. With current arrays, such a source must lie within the dark shaded area of the diagram at upper right.

Milliarcsecond-scale imaging is posible only for sources with brightness temperatures in excess of 10^6 K, and is thus restricted to the most energetic Active Galactic Nuclei and non-thermal stellar sources. Resolution of 10 mas is just achievable at 10^4 K, corresponding to the most intense, optically-thick thermal sources, such as ultra-compact HII regions. For sources below 10^3 K, the best

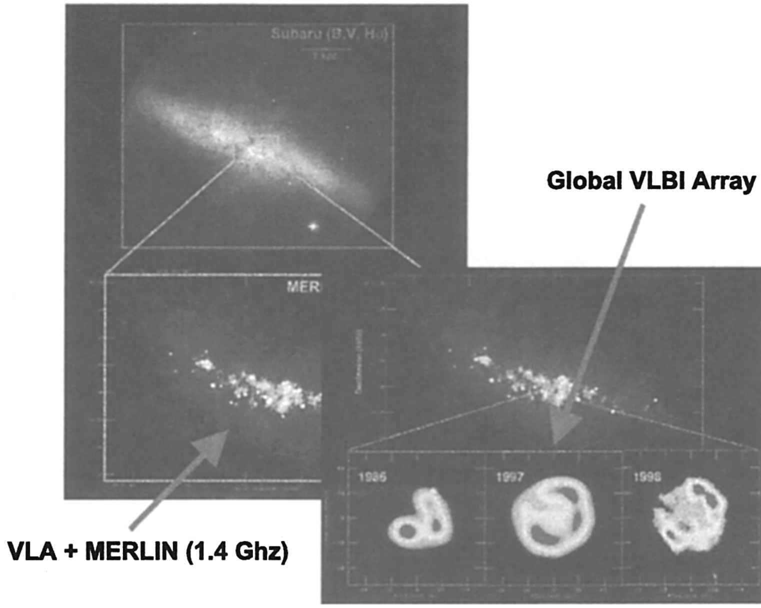

Figure 3. These radio images of the starburst galaxy M82 demonstrate the compelmentarity of existing radio interferometer arrays; covering baseline of tens of kilometer (VLA), hundreds of kilometers (MERLIN) and thousands of kilometers (Global VLBI). Optical image, NAOJ and the Subaru Telescope, radio images (McDonald et. al., this volume).

resolution is 100 mas. This is an interesting fiducial point in (T_b, θ) space - just sufficient to detect and resolve the few largest angular diameter stars, nearby red giants.

Figure 2 also demonstrates an important feature that will be an important element of design of future arrays - the complementarity of the VLA, MERLIN and the Global VLBI array. Together these arrays yield information on emission over a broad range of brightness and angular scale. This is illustrated in Figure 3, which shows radio images of the central region of the nearby starburst galaxy M82 (references). Combined VLA and MERLIN data show the diffuse synchrotron disk as well as the bright compact constituents of the galaxy (young supernova remnants and HII regions). Global VLBI observations allow us to focus in and map the expansion of individual supernova shells.

3. Future Prospects

3.1. The Next Decade

Clearly the frontier for radio interferometry is sensitivity, to work toward the unsampled lower left portion of Figure 2. Over the next decade upgrade programs on existing arrays will achieve order of magnitude improvements in continuum sensitivity. The enhanced (EVLA) and enhanced MERLIN (e-MERLIN) will have increased continuum bandwidth, from current ~100 MHz to several GHz

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at short wavelengths. Advances in recording technology over the next several years, and the application of long-distance fibre optics toward the end of the decade, will bring several GHz bandwidth to VLBI.

The New Mexico Array, planned for the latter part of this decade, will extend the VLA up to baselines of several hundred kilometres, providing resolution of 10's of mas at brightness temperatures of a few 100 K.

The effect of these improvements are indicated in Figure 2. The capabilities of radio observations are significantly advanced. Large numbers of sources will be studied that are inaccessible to todays instruments. However, milliarcsecond imaging at brightness temperature of a few K, required to image the continuum disk emission from high redshift galaxies, and spectral line sensitivity to allow imaging of the interstellar media of primordial galaxies will remain beyond the capability of present arrays. A large step in raw collecting area is needed.

3.2. Beyond 2010: The Square Kilometre Array

Over the past several years an international community of scientists and engineers has emerged with a common goal to solve the technical challenge required to construct a giant radio telescope with a collecting area of one square kilometre. The Square Kilometre Array (SKA) will have a hundred times more collecting area than the VLA, providing sensitivity of a few nanoJy in the centimetre/decimetre wavelength continuum.

An international consortium of institutes representing eleven countries is engaged in research into enabling technologies with a goal to begin construction of the SKA around 2010. The SKA will be an interferometric array operating at wavelengths from about 2 metres to 1.5 cm, with baselines ranging from a few hundred metres to thousands of kilometres (thereby providing the complete baseline coverage of the merged VLA, MERLIN, and global VLBI). A sample array configuration is shown in figure 4, and the area of (T_b, θ) parameter space that will be opened up by the SKA at its short wavelength limit is shown in Figure 5. By combining interferometry and phased-array receiver technology, the SKA will, despite its high resolving power, achieve a large field of view (1° at λ21 cm). The Square Kilometre Array will be the world's premier astronomical imaging instrument.

The wavelength range of the SKA spans the transition from emission dominated by non-thermal processes at long wavelengths to thermal radiation processes at the short wavelengths. With the combination of sensitivity, wide field of view and high angular resolution, the SKA will image the interstellar media and magnetic fields of galaxies to high redshift. Measurements of atomic hydrogen emission and continuum emission from galaxies will trace the star formation history of the Universe from primordial galaxies to the present. In our own Galaxy star formation processes and phenomena in the gaseous ISM will be studied on linear scales down to a few A.U. Millions of stars will be detected as radio sources, allowing, for example, imaging of protostellar and protoplanetary disk on sub AU scales, the initial mass function of massive stars in our own and other galaxies to be measured, the surfaces of stars to be directly imaged. In combination with next-generation space VLBI missions, the SKA will provide sufficient sensitivity to image, at micro-arsecond scales, the thermal emission from hot, x-ray emitting accretion disks in AGN cores.

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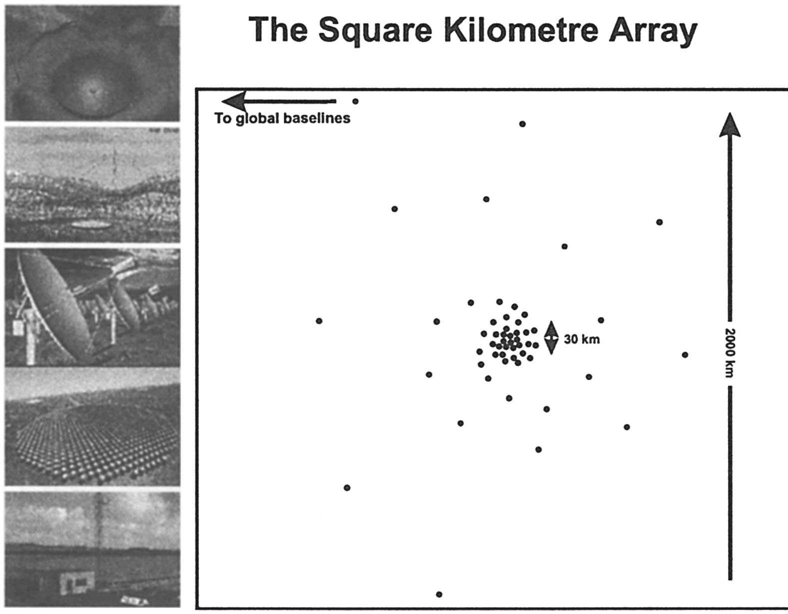

Figure 4. A possible array configuration for the Square Kilometre Array. A consortium of institutes from eleven countries are working on technical concepts (left) for the Square Kilometre Array telescope.

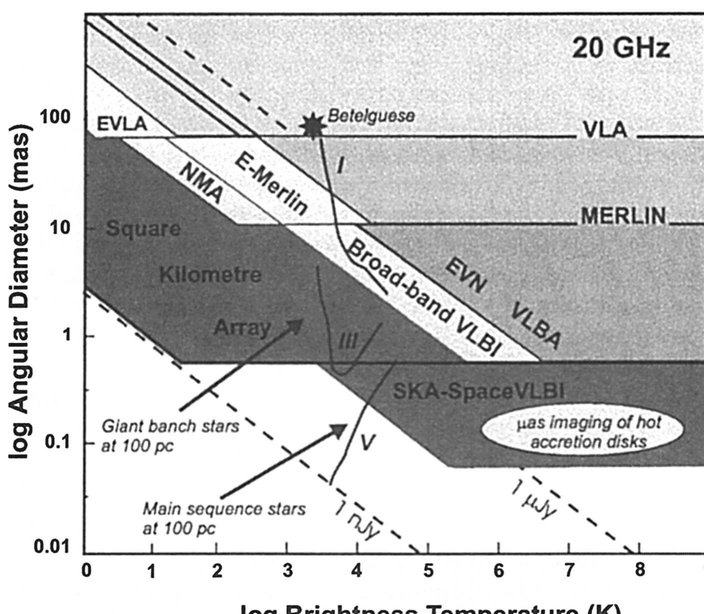

Figure 5. Brightness temperature - angular size parameter space opened up at the short wavelength limit of by the Square Kilometre Array. Tracks for supergiant (I), giant (III) and main sequence (V) stars at 100 pc distance are shown for comparison.