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SCIENTIFIC JUSTIFICATION for the AST *

The Parkes telescope was commissioned by Lord de Lisle exactly 19 years ago. In the two decades that have passed the two branches of world science which have developed most dramatically have been molecular biology and astronomy.

For unravelling the helical structure of DNA Watson and Crick were awarded the Nobel Prize in 1953, and that started the avalanche in molecular biology and genetic engineering that has swept through the last two decades.

Ryle was awarded the 1974 Nobel Prize for the development of large radio telescopes based on aperture synthesis (first proposed by Pawsey in 1947). Hewish was also given the Nobel Prize in 1974 for the discovery of pulsars. In 1978 Penzias and Wilson gained the Nobel Prize for their detection of the heat left over from the Big Bang which started the Universe 20 billion years ago. They could equally well have won the prize for their launching in 1969 of the new field of interstellar chemistry.

The tremendous growth we have witnessed in astronomy from planet Earth, from orbiting telescopes and from probes visiting other planets continues in full flood. If our astronomical ancestors could scan the current issue of the *Astrophysical Journal* they would extract only a glimmer of meaning from the titles, but their principal reaction would be one of incredulity.#

Companion papers in this Executive Seminar have evoked the incredible energy released by quasars, on the edge of the observable Universe, and described the truly fascinating phenomena of white dwarfs, supernovæ, pulsars, black holes and the enigmatic "X-ray objects" which signal the spectacular death of a massive star into unbelievably condensed states of matter. A third paper dealt with the seething cauldrons of stellar genesis in the icy near-vacuum of interstellar space. We could fill the rest of this seminar with discussion of the amazing ferment in astrophysics today. But our purpose is more to anticipate the science of the 1990s, for which the astrophysics of 1980 gives us a delicious foretaste.

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* To be presented at the CSIRO Executive Seminar, December 1980

\# With apologies to Carl Sagan

Astronomy, the oldest science, has reached a new maturity. We no longer talk of optical astronomy or radio astronomy, partial views of the Universe through the two windows where our atmosphere is transparent to electromagnetic radiation. What we witness today is a unified astronomy, where measurements of gamma-rays, X-rays, UV, light, heat and radio emissions are the jig-saw pieces which are *all* needed to solve the puzzles how the Universe began, how and when it will end, how galaxies form and evolve, how stars are born and how they die, ...

Twenty years ago most of what we have heard so far in this Seminar would have been regarded as wild speculation. What we must direct our minds to now is the question of what astronomy is going to be like in 1990, and what contribution will Australia be making to this seminal science? Wild speculation is not my forte, and I am not going to attempt to predict the state of astronomy in 1990.

But we can make some general predictions. Astronomy is a science in which exploration plays a paramount role. Its development in the next decade will be marked by increases in sensitivity, angular resolution and spectral coverage. Every major step in these three areas has led to new science. From the time Galileo invented the telescope and found the moons of Jupiter, new instrumentation has always uncovered new science. Science that had not been foreseen when the instruments were conceived. In astronomy, the unexpected is to be expected. That has been dramatically true in the last two decades. The incredible results from the HEAO-B X-ray telescope confirm this. We have this month seen the close-up pictures of Saturn's rings from the Voyager spacecraft. The launching of the 2.4 metre diameter Space Telescope in 1986 (or thereabouts) will be no exception to the rule.

Our purpose at this Seminar is to ponder what instrumentation Australia might build during the 1980s to produce the new science of the 1990s. The range of options open to our imagination is unlimited. In the Big Science of astronomy any solution will be expensive. Australia has international obligations here. We sit on a favoured observing platform in the southern hemisphere, with geological and political stability. One of our greatest natural resources is our privileged view of a collection of unique astronomical riches - the major part of the Milky Way, the nucleus of our Galaxy, the nearest external galaxies, the nearest radio galaxies, ...

ASTEC and the Minister of Science's Advisory Committee on Astronomy (AAC) have already expressed their views. ASTEC reported to the Prime

Minister in 1979[a] and the AAC reported to the Minister in 1980[b]. Both bodies agreed that the next major development in Australian astronomy should be a large radio telescope as proposed by the Steering Committee for the Australian Synthesis Telescope.

When I discuss this question with my colleagues in Europe and North America I get the same clear answer. They point to a major gap in world astronomy in 1990 unless Australia builds a sensitive, high definition radio telescope on the ground. For southern hemisphere ground-based support at radio and optical wavelengths is essential to complement the wealth of new astrophysical information coming from satellites instrumented for the infrared, ultraviolet, X-ray and gamma-ray portions of the electromagnetic spectrum - for those wavelengths where the atmosphere is opaque. Satellite-borne telescopes at these wavelengths can observe the *whole* of the sky. But the great array of northern hemisphere optical and radio telescopes cannot complement and support any satellite observations in the southern sky.

In recent years optical astronomy in the southern hemisphere has been well endowed. The magnificent 4 metre Anglo-Australian Telescope (AAT) on Siding Spring Mountain cost $16 million in 1973. To build it today would cost $35 million. The AAT and similar telescopes in Chile provide the necessary ground-based support in the optical band for the space programs of the 1980s and 1990s. In a few years the ANU will also be adding its 2.4 metre thin-mirror telescope to the already impressive range of optical telescopes.

But where will be the southern hemisphere ground-based support through the radio window in the atmosphere? Not in South Africa. Not in South America. Perhaps in Australia? Perhaps.

Astronomical Instrumentation in the 1980s

Any major instrument in the southern hemisphere will take more than five years to fund and to build. Where will it fit into the world astronomical scene in the late 1980s?

We can compare the performance of telescopes in terms of their beamwidth and their sensitivity. For telescopes in different wave bands we need to compare their beamwidths. The current and anticipated beamwidths

(a) "The Next Generation of Australian Telescopes, ASTEC Report, March 1979
(b) "Astronomy in Australia - Developments in the 1980s" - AAC Report July 1980

of telescopes in the various parts of the electromagnetic spectrum are listed in Table 1.

At southern latitudes a high resolution radio array is clearly needed in the second half of the 1980s to provide the essential ground-based support for

- the planned X-ray Observatory, with a target of resolution of 1" arc
- the 2.4m Space Telescope, with resolution of 0.1" in the optical and UV bands
- the Satellite Infra-red Telescope Facility (SIRTF) with a resolution of 2" arc at 10 μm and 20" at 100 μm.
- the planned gamma-ray observatory

It is likely that in this space-support role the southern latitude radio array would find its best opportunities to carry out the science of the unknown. To fulfil this role the radio array would need to achieve an angular resolution of $\approx$1" arc at a wavelength near 3cm.

Known science which such an array could carry out is listed in Table 2. The topics listed are representative, not complete. For many of these objects partial synthesis would be adequate, with no risk of confusion from nearby objects of the same type. Resolution near 1" arc is also needed as a prerequisite for satisfactorily interpreting VLBI maps.

With a 1" arc beam the resolution of the radio array would match exactly that of the 4 metre Anglo-Australian telescope. This would greatly enlarge the scope for cooperative projects between the two telescopes.

A compact filled-array configuration is another vital requirement, for investigation of a number of classes of objects, such as:

- 1.4 GHz hydrogen line mapping of spiral arms in galaxies, with resolution $\approx$20" arc
- mapping of H II regions at a frequency of $\geqslant$10 GHz where they are optically thin
- Investigation of structure, polarization and spectral index of SNR at a frequency near 10 GHz where the Faraday rotation is sufficiently small to be realiably disentangled
- mapping of compressed gas shells around SNR

A compact array (not filled) is needed to determine kinematic distances of galactic objects from measurements of galactic 21cm absorption, a method which has already been effectively exploited at Parkes and could be extended considerably with a new array.

<u>Why does a Radio Array have to be so Big?</u>

We need to look briefly at two reasons why a radio array has to be so big and so expensive. The first concerns the angular resolution, or definition, of a radio telescope. The second concerns the sensitivity.

1. Definition, or Angular Resolution

For any telescope the definition is set by the ratio of the diameter D to the wavelength λ. The higher the value of D/λ, the greater the ability of the telescope to separate two very distant objects in close proximity.

For radio waves λ is very large, and so D must be large to achieve a large value of D/λ. A beamwidth of 1" arc corresponds to D/λ = 200,000. A radio telescope operating at a wavelength λ of 3cm then requires D = 200,000 λ = 6 kilometres.

The Culgoora radioheliograph has a diameter of 3 kilometres; at its shortest wavelength of 92cm it has D/λ = 3260. The Mills Cross at Molonglo has a length of 1.6cm; at its wavelength of 36cm, D/λ = 4444. Thus the proposed new array with D/λ = 200,000 provides a major step forward in definition on the radioheliograph or the Mills Cross. [Figures needed for Fleurs Synthesis Telescope.]

You will be asking why the radioheliograph is only a ring, the Mills Cross is only a pair of strips, the Fleurs telescope has two strings of small dishes? That is explained by Bob Frater in the companion paper (ASTDOC 54) when he explains how to synthesize an aperture.

2. Sensitivity and Collecting Area

One reason why we don't have to build a complete dish 6km in diameter concerns sensitivity. Fortunately we don't need all the acreage of a 6km diameter dish to achieve adequate sensitivity.

The power of radio signals reaching the Earth from space is incredibly low. The intensity unit we use is the Jansky, equal to 10^{-26} watts/square metre/Hertz. A radio telescope designed for the late 1980s and 1990s will need, to probe the utmost reaches of the Universe, to have a sensitivity of about 10 micro-Jansky*, or 10^{-31} watts/square metre/Herz.

A good TV receiver can detect a signal of 10^{-20} watts/Hz and has a bandwidth of 5 MHz. If we were to use it as the receiver on a radio telescope we would need to build a telescope with an aperture of about 40 million square metres (10 thousand acres) to achieve a sensitivity of 10^{-31} watts/square metre/Hertz with a 1 second exposure. This corresponds to a dish 7km in diameter.

Such an area is out of the question. We must reduce it, and can reduce it. By two means - (a) by building better receivers and (b) by making much longer exposures.

(a) Building better receivers

The receivers we are currently developing at the Division of Radiophysics will have a sensitivity twenty times better than our quoted TV receiver. The bandwidth of the "back end" designed for our array is 12 times wider than that of the TV receiver. These two factors will reduce the area by a factor 20 x $\sqrt{12}$ = 70x.

(b) Longer exposures

In elementary physics we can make a measurement N times and reduce our errors of measurement by N. In a strictly analogous way the radio astronomer can average his signals for N seconds and improve his sensitivity by $\sqrt{N}$. As Bob Frater explains in his companion paper [ASTDOC54], earth rotation aperture synthesis by its very nature implies a large value of N, typically 40,000 seconds for a one-day synthesis. This reduces the area required by a further factor of 200.

With state-of-the-art receivers and the long averaging times of aperture synthesis, the area required for a sensitivity of 10^{-31} watts/square metre/Hertz reduces to 2850 square metres. By using two receivers for orthogonal polarizations we can reduce the area required to 2000 sq.m. The 64 metre diameter telescope at Parkes has an effective collecting area of 1800 m^2, which is already 90 percent of the area we require. Thus the combination of the 64m telescope with a number of smaller dishes over a 6km baseline will achieve the desired sensitivity and definition.

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* As used here, the rms output noise is 10μJy.

TABLE 1

WORLD ASTRONOMY in the 1980s

Spectral Domain	Angular Resolution: Epoch 1980		Epoch 1985		Space or Ground Based
	Arcsec	Instrument	Arcsec	Instrument	
γ-ray	(5°)	Cos B Satellite	(8')	γ-ray Observatory Satellite	Space facilities
X-ray	3"	HEAO-B 30 arc min field	≤1"	X-ray Observatory Satellite	
UV	1"	Good sites	0".1	Space Telescope (2.4m)	
Visual	0".5	Chile, Hawaii	0".1	Space Telescope (2.4m)	
IR 10μm	0.5	Good sites	2"	SIRTF Satellite	
100 μm	?	?	20"	" "	
mm-wave	30"	Onsala 20m dish	20"	MPI 30m dish	Ground based
	4"	Hat Creek Interferometer	0".8	Pic du Bure Interferometer	
Radio 13mm	0".1	VLA	0".1	VLA	
21cm	1".5	VLA	1".5	VLA	
11cm	0".2	Jodrell Interferometer			
2.8cm	0".0015	VLBI	<0.001	VLBI	Ground and Space

TABLE 2

Known Science for a Southern Radio Array

Class of Object	Angular size θ (arcsec)	Frequency (GHz)
Extended cores of radio galaxies	$0.01'' < \theta < 2''$	3 to 10
Jets in radio galaxies	$1'' < \theta < 150''$	5
Compact H II regions	2"	10
Knots in SNR	2"	5 to 10
Cells in SNR	20"	5 to 10
Planetary nebulae	$\geqslant 2''$	10
SiO masers (distribution/components)	2" / 0.01"	43
OH masers (distribution/components)	2" / 0.03"	1.6
H_2O masers (distribution/components)	50" / 0.001"	22
Galactic centre sources	$\leqslant 10''$	5
Sun	?	?
Planets	?	?