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SPIN-OFF FROM BASIC SCIENCE: THE CASE OF RADIOASTRONOMY

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Two of the chief economic effects associated with basic research are technological spin-off and manpower-training benefits. This article investigates the specific example of British radioastronomy and considers the implications for science policy

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We argue in this article that there is an urgent need to assess the nature and extent of the outputs from basic research, especially Big Science. Two main types of spin-off associated with such research are identified – technological spin-off and manpower-training benefits. We then look at the case of British radioastronomy, examining how important these economic benefits have been. The evidence presented here suggests that the latter has probably been the more important, a conclusion which, if correct, means that in future work on the economic effects of Big Science, greater attention should be given to the question of manpower-training than has previously been the case. Finally, some policy implications of these findings are discussed.

The need for science policy

In recent years Western governments have increasingly been forced to search for ways to construct overall policies for scientific research that will, on the one hand, ensure that the scale of research activity in different areas of science is matched to the changing level of resources available and, on the other, allocate priorities in such a way that the outputs from scientific research are more in line with the requirements of society as well as the needs of science, and are achieved as efficiently as possible. As the economic climate facing basic research has deteriorated in the 1970s, so the need for an explicit science policy has grown.

Between 1945 and 1970 scientific research flourished. In this period a whole range of new scientific specialities grew up and developed, many of these coming to demand increasingly sophisticated equipment. While it was relatively easy to

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accommodate such claims for resources in the years when the science budget was rising by 5 or 10% *per annum* (as in most Western countries until the early 1970s), it has become far more difficult in today's much harsher economic climate, where growth rates of, at most, a few per cent are all that can be expected.

The problems are particularly severe for the so called 'Big Sciences' – space research, astronomy and high-energy physics – where a single new facility or project can cost upwards of tens of millions of pounds. As early as the 1960s the scientific community began to discuss the implications of sophisticated, high-cost research for the structure and organisation of science funding. The eminent American physicist, Weinberg, was one of the first to enter the debate, arguing that explicit criteria for scientific choice need to be formulated if decisions on the funding of research are to be made more 'rational'. Since then the costs of scientific research in general have continued to soar and the case for an assessment of the benefits from Big Science has grown stronger. Scientists, particularly those engaged in expensive projects, will in future find it advantageous to demonstrate that their work yields not just 'good science', but also some positive benefit for society at large. This view has been stated particularly eloquently by Weinberg (1963 p 171):

'It is as much out of a prudent concern for their own survival, as for any loftier motive, that scientists must acquire the habit of scrutinising what they do from a broader point of view than has been their custom. To do less could cause a popular reaction which would greatly damage mankind's most remarkable intellectual attainment – modern science – and the scientists who created it and must carry it forward'.

If Big Science proves unable to demonstrate any benefit apart from providing a comfortable and intellectually satisfying occupation for a few thousand researchers, then its case for continuing to consume millions of pounds would not appear to be very strong. However, as some previous work has indicated and as this article will argue, there are demonstrable benefits even from a basic science like radioastronomy. The question is whether such benefits are sufficiently large to justify continued funding of science in the style to which it has become accustomed.

Rationale for basic research

The task of assessing the output from basic research is extremely difficult, particularly since the products of scientific endeavour may take a variety of forms: new scientific knowledge, new scientific problems or new practical ideas and techniques of more direct benefit to society. Though perhaps difficult to 'measure', there can be no doubt that there is an output of some kind from science. The various outputs from scientific research can be classified into two main categories, using Weinberg's distinction between 'internal' and 'external' criteria for scientific choice (Weinberg 1963 p 163):

'Internal criteria are generated within the scientific field itself and answer the question: How well is the science done? External criteria are generated outside the scientific field and answer the question: Why pursue this particular science?'

Though it is clearly important to consider both sets of questions in any overall evaluation of science policy, we are concentrating here on the latter. In answering the question 'Why fund this science?', a number of different answers might be given:

(1) It is a branch of science that contributes a great deal to our understanding of other areas of science, i.e. it is more *'fundamental'* than others.

(2) It is a branch of science that is particularly important in helping human beings understand and make sense of their natural and social environment, i.e. it is *culturally* significant.

(3) It is a branch of science that provides vital ingredients for material progress and welfare, i.e. it is of central *economic* importance.

Do these answers provide sufficient justification for the current level of support for Big Science? To take the first two arguments, it should be noted that *all* basic research, and not just Big Science, is to a certain extent 'fundamental' and 'culturally important'. What is not clear is whether Big Science is so much *more* fundamental or culturally important to justify a level of support typically one or two orders of magnitude greater than for other areas of basic science. We shall therefore concentrate here on the third possible justification of Big Science – its economic importance. In previous research (e.g. ESA 1978, Schmied 1977) various authors have examined high-energy physics and space research, and claimed to find significant economic benefits arising from these activities. In this article, we look to see whether similar spin-off arises from radioastronomy.

Dimensions of economic spin-off

According to its proponents, Big Science invariably creates a significant economic impact on society. The crucial feature that distinguishes Big Science from Little Science is the concentration of resources on a few major research facilities, with new equipment generally demanding significant R and D at the frontiers of technology. There are three main forms of economic benefit often claimed to be specifically associated with Big Science (although some would argue that all three can be obtained with equal facility and at far lower cost from Little Science). First, Big Science is held to be more likely to lead to the development of original, fundamental scientific ideas, which subsequently form the basis of radically new innovations. Secondly, it is argued that Big Science generates various technological benefits, and hence economic gains, to firms supplying equipment to scientific researchers.

These vary in magnitude from the benefit associated with producing a major, new piece of equipment to those stemming from minor improvements to standard instruments suggested by their scientific users. The third type of possible economic benefit involves the training of highly skilled researchers who then go on to utilise their skills in R and D at the frontiers of technology, thus creating economic benefits for their subsequent employers.

These, then, are the three main areas of possible economic benefit we will consider when looking at external criteria for supporting radioastronomy. The first two can be termed *technological* benefits (or 'technological spin-off') and the third '*manpower-training*' benefits. While most previous studies have put the stress on technological spin-off, we will argue that manpower-training benefits are also very substantial and may be, for radioastronomy at least, the more important of the two forms of economic benefit. However, we turn first to technological spin-off.

Technological benefits

Before one can even attempt to evaluate the technological spin-off from radioastronomy, the first task must be to identify the potentially important areas of spin-off. This has been one of the main objectives of a project carried out at the Science Policy Research Unit over the last two years on the assessment of a number of Big Science centres. In a series of interviews at the two British radioastronomy observatories at Cambridge and Jodrell Bank, we asked staff to identify instances of spin-off associated with their work, and with that of other radioastronomers.' Because of the difficulty of examining in detail *all* the instances of possible spin-off cited by them, we concentrate here on those cases that appear to involve the most substantial technological benefits.

The next stage was then either to approach the firms involved and ask each for their views on the extent of spin-off involved or, if the spin-off had yet to reach the stage of commercial exploitation, to consult the relevant literature and any experts in the field, in order to ascertain its likely future importance. Radioastronomers and their technical staff were agreed that one of the main types of spin-off has arisen through direct benefits to capital equipment suppliers, particularly to the contractors responsible for the construction of the major telescopes at Jodrell Bank and Cambridge.

To take the Cambridge instruments first, the 1 mile telescope was constructed by the British subsidiary of Blaw Knox, which had already built several tracking stations and the telescopes in the United States. The firm was therefore able to re-use existing technology, with the result that the Cambridge project required virtually no major new technological development. This ensured that the project could be completed relatively quickly and cheaply. So while it was a success from the scientific point of view, as the firm itself stated, it did mean that there was no technological spin-off from this contract in the area of communications, nor even in the field of radioastronomy (this was the only radio telescope the British subsidiary built). In the case of the other main Cambridge telescope, the 5 km interferometer, some technological innovation was required (in, for example, servo techniques to improve the pointing accuracy). However, Marconi, the contractor, was also able to re-use some of the technology from an earlier tracking station project, and therefore felt that overall it gained little economic benefit (over and above that of selling a product) from constructing this radio telescope – certainly no more than it would expect from *any* contract of this magnitude. As the project manager for this contract stressed:


The Cambridge 5 km radio telescope (photograph courtesy B Elsmore)

'As a general guide, I'd say that between 5 and 10% of our work for any large project results in new skills and techniques that will at some future time be directly transferable to another project ... Although much of the development work done for the 5 km project hasn't been re-used yet, it's gone into our library of skills ...'.

At Jodrell Bank, in contrast, the contractor does appear to have benefited rather more through direct spin-off to its work in the communications industry. The technology for constructing 'big dishes' was pioneered there by Sir Bernard Lovell and his consulting engineer, Sir Charles Husband. The experience gained in building the giant 76 m mark 1 telescope in the 1950s enabled Husband and Co. to tender for other big-dish contracts in Britain and overseas, in particular the Goonhilly receiving station. On the basis of interviews with the firms concerned, it would appear that there are perhaps three main benefits that the pioneering work by Jodrell Bank radioastronomers brought to the communications industry. First, they were responsible for the *idea* of big dishes, and for demonstrating that very weak signals could be detected in this way. Secondly, there were benefits in the actual *construction* of big dishes, with Husband gaining valuable experience from Jodrell Bank projects and initially establishing a reputation in this new area of technology. Finally, radioastronomers contributed to our knowledge on the *use* of big dishes. For example, the mark II telescope was one of the very first large pieces of equipment to be controlled by an on-line computer, demonstrating the enormous advantages that this brings. Since that pioneering work at Jodrell Bank, several hundred large communications dishes have been built around the world, performing an increasingly important function in the fields of telecommunications and defence systems. British firms, however, despite their early head-start in this area, failed to capitalise upon this lead – indeed, the most recent Post Office dish at Madley was constructed by Mitsubishi (although Marconi did supply the radio and communications equipment).

Benefits to suppliers

A second type of technological spin-off involved direct spin-off to instrument suppliers, and here developments in the field of parametric amplifiers have been particularly important. One firm, the Microwave Group of Ferranti, seems to have derived substantial economic benefit from its collaborative development work with Jodrell Bank. This collaboration was born in the late 1950s after Jodrell Bank had ordered from a rival company a number of parametric amplifiers (paramps), then a new product, only to find them far from satisfactory. Learning of these problems, a small group working nearby at Ferranti offered to build a prototype to Jodrell Bank's specifications, provided it was given any orders that subsequently arose. To this Jodrell Bank agreed, and Ferranti eventually produced a highly satisfactory prototype which, on testing at Jodrell Bank, met the specifications set by the astronomers. After producing the small number of paramps required by Jodrell Bank, the Ferranti group looked round to see whether this new product might have any other uses, and gradually developed several new devices based on the paramp, which are now crucial components in a wide range of Ferranti products, including military radar, tropo-links, satellite receiving dishes and mobile ground stations.

Ferranti appears to have derived four main benefits from its contract with radioastronomers. First, the early Jodrell Bank orders, though small, initially constituted some 20–30% of the Microwave Group's turnover, and therefore helped provide a sound basis for its future growth. Secondly, the contact with Jodrell Bank was a key factor in stimulating the development of an entirely new range of products, and hence in creating new market opportunities. Thirdly, Ferranti was able to utilise the nearby research facilities at Jodrell Bank to test new products quickly and rigorously. Finally, since radioastronomers were, at the time, at the very forefront of microwave technology, always requiring the ultimate in performance, there was a considerable transfer of knowledge and techniques. But although these various benefits were very real, two further factors must be taken into consideration when evaluating the extent of this particular spin-off from radioastronomy.

The first is that the impact on Ferranti has subsequently declined significantly. Over the last decade other paramp users, particularly in the field of defence, have become more demanding in their requirements than radioastronomers, and consequently it is military rather than university contracts that are now most influential in dictating the pace of innovative activity. The other factor that should be stressed is that, at the time of Ferranti's collaboration with Jodrell Bank, similar technological developments in paramps were taking place elsewhere *without* any stimulus from radioastronomers – in particular in the United States under the impetus of demands from the communications and defence industries. It is therefore arguable whether the overall development of paramps would have been any different without radioastronomy. Although the Jodrell Bank work had a major impact on the growth of the Ferranti Microwave Group, it cannot claim responsibility for the overall development of the paramp.

Re-use of equipment and techniques

A third type of technological spin-off concerned the transfer of radioastronomy equipment to areas such as medical physics, and in particular to tumour-detector technology. Professor Alan Barrett, a radioastronomer at MIT, was perhaps the first to realise that receivers of the type employed in radioastronomy could be used to determine with some accuracy subsurface temperatures within the human body. This has numerous potential applications in clinical diagnosis, including the early detection of breast cancer (which often shows up as an area of abnormal local heating). The great advantage of this technique of microwave thermography is that it involves passive, non-invasive sensing – it merely monitors the heat generated in the body – and therefore can be repeated as often as necessary without any radiation hazard or physical discomfort. Since 1974 Barrett and his colleagues have examined several thousand patients for breast cancer, successfully demonstrating the technique's use as a diagnostic tool (Barrett and Myers 1975, Barrett *et al* 1981).

However the economic benefits associated with microwave thermography are still largely in the future. Firms consulted by Barrett believe that there is no commercial market for microwave thermographs at present, although one German

Table 1 *The extent to which radioastronomy is perceived by scientists and technical staff as a technological stimulus to British industry*

	Sample size	*No. who feel the extent of the stimulus was:* *A great deal*	*Some*	*Little*	*Non-existent*	*Can't say*
Scientists	38	1 (3%)	17 (45%)	16 (42%)	1 (3%)	3 (8%)
Technical staff	7	1 (14%)	2 (29%)	3 (43%)	1 (14%)	0 (0%)
All staff	45	2 (4%)	19 (42%)	19 (42%)	2 (4%)	3 (7%)

firm is carrying out some development work so that it will be well placed if any market opens up in the future. As yet, the economic benefits from this development remain uncertain, but it would appear that few will be directly attributable to British radioastronomy.

Finally, a number of instances of technological spin-off involving the transfer of radioastronomy techniques were identified in our interviews. One of these involved the precise measurement of distances: this has been used with some success to detect movements of the earth's crust in earthquake zones, but again this work has been pioneered by American rather than British radioastronomers. Also mentioned was the use of radio signals for the purposes of very precise navigation on the earth's surface, although it is not clear whether this will have any significant benefits outside the military field.

Overall, then, although our studies of the different aspects of technological spin-off from radioastronomy are by no means exhaustive, it would appear that the economic benefits have been rather limited – a conclusion supported by the responses made by staff of the two radio observatories to a question concerning the impact they felt radioastronomy as a whole has had on industry. As the figures in table 1 demonstrate, both scientists and technical staff were agreed that the level of technological impact by radioastronomy had not been very high: almost half thought that it was either 'little' or 'non-existent'. In fact, virtually all the astronomers interviewed justified the generous support of radioastronomy in terms of either its contribution to scientific knowledge, or the flow of trained postgraduates into high-technology jobs. Furthermore – and perhaps surprisingly given previous work which suggests that considerable economic utility is gained by firms employed on Big Science contracts (Schmied 1977, ESA 1978, Evans 1976) – this opinion was shared by the companies most closely connected with radioastronomy in Britain. Both they and the university scientists were in no doubt that the more substantial economic gains from radioastronomy have taken the form of manpower-training benefits.

Manpower-training benefits

To what extent does radioastronomy provide significant benefits to the economy in the form of highly trained scientists for industry and government? To answer such a question, two sets of data are ideally needed; first, one must ascertain the numbers and percentage of radioastronomy students moving to industry, and establish whether these figures are any different from those for other areas of science; and secondly, one needs to discover whether a training in another, less costly, area of science would furnish students with a similar range and level of skills.

Table 2 *Percentage distribution of former radioastronomy postgraduates by first and present job*

Nature of employment	*Ph D students* FIRST JOB (*n*=277)	PRESENT JOB (*n*=182)	*M Sc students* FIRST JOB (*n*=58)	PRESENT JOB (*n*=37)
Academic (university or polytechnic)	55%	46%	49%	31%
Government basic research (including SRC centres)	11%	13%	6%	6%
Government R and D (including management)	12%	16%	4%	10%
Industry	17%	20%	29%	35%
Other	4%	5%	12%	18%

Table 3 *Skills acquired by postgraduates during their radioastronomy training. Percentage of students who regarded themselves as having developed these skills 'to a great extent' or 'to some extent' while a postgraduate student*

Skill	*Ph D students (n=182)*	*M Sc students (n=37)*
Individual initiative	93%	77%
Capacity to undertake original scientific work	91%	63%
Ability to tackle and overcome complex problems	89%	71%
Ability to communicate effectively	72%	49%
Expertise in computing	71%	71%
Expertise in electronics	65%	66%
Ability to work as a member of a team	64%	43%

In attempting to provide these data, we sent postal questionnaires to virtually all the former postgraduate students from the two British radioastronomy observatories. The results (table 2) show that between 1945 and 1978 a total of 277 Ph D students and 58 M Sc students were trained at Jodrell Bank and Cambridge. Our questionnaire survey elicited a response rate of just over 75% – a highly satisfactory figure given the technical problems of tracking down people who have been working an average of 10 years (and some as many as 20 or 30 years) since completing their studies. Three main sets of questions were asked:

(1) What skills and expertise were developed during postgraduate study?

(2) What jobs have been held since completion of postgraduate work? (Data for this are given in table 2.)

(3) In those jobs, which of the skills developed as a student have proved most useful?

While the responses to these questions suggest (as we shall see below) certain conclusions about the value of the skills imparted to radioastronomy students, they unfortunately do not reveal the entire picture on the *volume* of manpower flows into industry. The problem is that there exist no comparable data on subsequent employment for other scientific disciplines, in particular for Little Science. The only data available are for the 'first destinations' of students, or for their employment just two or three years after finishing their courses – before many of them have settled down to a permanent career. Furthermore, such data provide only a static 'snapshot' of a cohort of students who graduated in one particular year, and they do not reveal *changes over time* in the employment as our figures do. The only data that can be compared reasonably well with other areas of science are, however, those for first destinations, and here the figures for radioastronomy (17% of Ph D students take their first job in industry) are slightly higher than those for physics (14%) and all science (13%).

However, it is not sufficient to look solely at the *volume* of manpower flows; one must also examine the *quality*, and in particular the types of skills transferred. When one does this, postgraduate training in radioastronomy is clearly seen to be associated with some highly specific skills of direct use to industry, particularly in certain areas of high-technology R and D.

Although there have been changes with time, postgraduate training in radioastronomy has involved a variety of tasks ranging from the construction of receiver equipment (perhaps involving sophisticated electronics) and the use of this equipment on a radio telescope (often as part of a large research team), to the development of computer programs and mathematical techniques for processing and analysing data. Having discussed with radioastronomers the sorts of skills a postgraduate would be likely to acquire, we asked former students to evaluate the extent to which they developed various skills during their postgraduate work. Those cited as having been most developed are listed in table 3. It can be seen that a very high percentage of respondents claim to have acquired these particular skills as postgraduates.

If we then analyse the response of students now working on R and D in industry and government to the question of how useful these skills have been in their jobs, it emerges that there are substantial benefits from a training in radioastronomy. The data in table 4 show that not only have several general skills (of the type one might expect from any postgraduate research) been found useful – for example, individual initiative, the capacity to undertake original scientific work and the ability to communicate effectively – but so have several skills which are apparently rather more specific to radioastronomy. Of the former Ph D students now working in industry, no less than 85% have found their training in computing 'useful' or 'very useful', 65% their electronics training, 50% their expertise in radio systems and 40% their knowledge of radioastronomy techniques. Furthermore, some of the skills associated with Big Science research, such as organisational and supervisory ability, and the ability to work as a member of a team, have also been useful in many cases.

One might wonder what it is about the type of

Table 4 *Relationship between present employment and skills acquired as a postgraduate student. Percentage of former postgraduates now working in industrial and government* R *and* D *who find the skills they acquired as students 'useful' or 'very useful'*

Skill	*Ph D students* INDUSTRIAL	*Ph D students* GOVERNMENT	*M Sc students* INDUSTRIAL	*M Sc students* GOVERNMENT
Individual initiative	90%	87%	73%	75%
Expertise in computing	85%	70%	91%	100%
Ability to tackle and overcome complex problems	80%	94%	73%	50%
Ability to communicate effectively	78%	79%	55%	25%
Ability to work as a member of a team	65%	71%	36%	50%
Expertise in electronics	65%	65%	64%	25%
Organisational and supervisory ability	50%	53%	9%	0%
Expertise in radio systems	50%	44%	45%	25%
Capacity to undertake original research	48%	82%	36%	75%
Knowledge of radioastronomy techniques	40%	53%	36%	25%
Ability to appreciate commercial potential of research	25%	15%	36%	0%
Ability to publish	21%	68%	36%	25%
Understanding of astronomy theory	13%	24%	0%	50%
Others	10%	15%	0%	0%

employment chosen by these former radioastronomers that leads their student skills to be so useful. The explanation is that many have migrated to a number of specific industrial areas in which their skills can be put to direct use. Some of them, for example, are involved in the design and construction of antennas and electronics equipment in the telecommunications industry; some are employed in defence work on communications and surveillance; and others are using their computing skills in problems involving the separation of a weak signal from background 'noise' in areas such as medical physics, satellite-mapping and automatic fingerprint recognition. So while the amount of technological spin-off from radioastronomy to industry may have been limited, there have undoubtedly been substantial manpower-training benefits. Some quantitative evidence for this is provided in table 5. As can be seen, most students entering industry or government have spent the bulk of their working years in high-technology areas intimately related to their previous training. Altogether, radioastronomy students have spent 11% of their subsequent careers in computing, 8% in telecommunications and radar, 5% on wave propagation problems, and so on. We would argue that it is the close relationship between the skills acquired by radioastronomy students and their subsequent utilisation in certain areas of high-technology R and D that is responsible for the undoubted economic impact of radioastronomy.

Conclusions

This article began by arguing that there is a growing and increasingly urgent need for a more systematic assessment of basic research, particularly of the Big Sciences where capital and recurrent expenditures can be of an order of magnitude higher than in other areas of science. The aim has been to evaluate the economic impact of one area of Big Science in order to ascertain whether it has given rise to economic benefits of such a magnitude as to justify, in terms of Weinberg's external criteria, the level of financial support it receives.

The strong evidence presented here provides, we would maintain, a sufficiently strong foundation on which to base a number of policy conclusions, not only for radioastronomy but also perhaps for Big Science in general. To take radioastronomy first of all, it is clear that the level of technological spin-off has been rather limited, at least in the opinion of most of the scientists, technicians and firms concerned. In the words of a senior manager in one of the world leaders in the satellite and space communication industry.

'Radioastronomy got us off to a flying start in the early years between 1961 and 1963. It laid the foundations of our work – giving us the theory of big dishes and their method of construction, as well as providing us with sensitive receivers – but that is all. After that, it has gone its own way . . . Since then, as far as I can remember, there has been no major development in radioastronomy that has been taken up in satellite communications. We are two different branches of the same subject'.

What has yet to be fully established is whether the somewhat meagre technological benefits to British industry can be explained in terms of the nature of radioastronomy or Big Science itself, or whether they must be attributed to prevailing economic and social conditions, particularly those in Britain, which have been such that potential spin-off has not been translated into actual economic benefits. Some of the instances of spin-off

Table 5 *Number of 'man-years' spent by former postgraduate students in 'Research, design and development'† jobs as a proportion of 'man-years' in all forms of subsequent employment*

	Ph D students (*n* = 182)		*M Sc students* (*n* = 37)		*All students* (*n* = 219)	
Total number of man-years employment since finishing postgraduate study	1826		261		2087	
Total man-years spent in:						
Government R and D‡	328	(18.0%)	11	(4.2%)	339	(16.2%)
Industrial R and D	268	(14.7%)	90	(34.5%)	358	(17.2%)
Total R and D	596	(32.7%)	101	(38.7%)	697	(33.4%)
Total man-years spent in the following areas of R and D:						
Computing, etc.	196	(10.7%)	31	(11.9%)	227	(10.9%)
Telecommunications, antennae engineering, etc.	138	(7.6%)	25	(9.6%)	163	(7.8%)
Wave propagation, etc.	85	(4.7%)	16	(6.1%)	101	(4.8%)
Electronics, etc.	66	(3.6%)	26	(10.0%)	92	(4.4%)
Image analysis, etc.	30	(1.6%)	2	(0.8%)	32	(1.5%)
Other	81	(4.4%)	1	(0.4%)	82	(3.9%)

† Excluding management of R and D (above the level of project leader).

‡ This excludes substantial numbers of scientists working in government establishments on basic research (principally on radioastronomy).

in other countries mentioned here suggest that it should be possible to strengthen the links between basic research and industry so that the possibilities for technological spin-off are increased. It is probably not without significance, for example, that the development of microwave thermography has taken place in the United States rather than in Britain, even though the latter was, at least initially, well ahead in radioastronomy; for in Britain, the links between basic research carried out in universities and the exploitation of any new technology it may generate are notoriously weak. For example, few British academics would, on developing a piece of equipment with economic potential, set out to exploit that equipment – perhaps by setting up their own firm – in the way that many of their American colleagues have done. This is not to say that there are *no* links between universities and industry in Britain, but rather that, for basic research in particular, the links may be weak relative to those in some other countries.

However, the main problem almost certainly does not lie in poor links between universities and industry, but within the British economy itself – in the degree of competition between firms, in the market towards which they choose to orientate themselves and in their propensity to develop products geared only to meeting narrow national needs rather than international demands (cf Pavitt 1980). Unless there is some considerable improvement in the conditions for ensuring that *potential* technological spin-off is translated into *actual* economic benefits to firms, it seems doubtful whether one will be able to justify the current levels of expenditure by Britain on radioastronomy in terms of technological spin-off alone.

A rather different conclusion seems to emerge from evaluating manpower flows into industry. Although the rate of flow of radioastronomy postgraduates into industry is only slightly greater than that for students from other scientific disciplines, analysis of the quality of the flow and, in particular, of the type of expertise transferred, points to the existence of quite substantial economic benefits for such areas of high-technology industry. The evidence here suggests that if an economic justification for the support of radioastronomy is to be found, it will centre primarily on the migration of highly skilled students to industry. This is certainly the view of Sir Martin Ryle, Astronomer Royal and Director of the Cambridge group, who has stated (Ryle *et al* 1971 p10):

'The most important practical contribution of our work is in the training of young men and women in the skills which go with research in an advanced field; many of them go into industry, where their experience is helping them solve the problems they meet'.

Perhaps more significant is that this is also the assessment of the operations manager of a firm responsible for the construction of one of the main British radio telescopes. In an interview, he made the following observations:

'Although there were spin-offs from the (radioastronomy) contract – as there tend to be from *all* our work – I could not honestly say that they could be used to justify such expenditure in terms of their giving a British company competitive technical advantages . . . This is not to say, though, that the Science Research Council should not take steps to make sure technological spin-off is maximised . . . But perhaps the biggest spin-off overall from radioastronomy is the trained graduates who come into the telecommunications and military field. We have had two particularly good people here, one of whom is an expert in antennae calculations. *We can use directly the specialised skills they gain in their radioastronomy research*' (emphasis added).

If further research shows in general that manpower-training benefits are as important in radioastronomy and perhaps in Big Science as our findings for radioastronomy suggest, this has at least two very specific implications for research policy. First, Big Science must continue to involve postgraduate students as much as possible, and this in turn implies that research should be carried out within, or at least in very close association with, universities and other academic establishments. This is an important consideration in that, in some areas of Big Science (especially high-energy physics), there has been a pronounced trend towards large national and international centres, with the result that there may be a danger of the links with universities being weakened and the quality of the training given to postgraduates diminished.

This leads to the second policy conclusion: where the links are maintained, and where students continue to be involved in research, efforts need to be made to ensure that students are still able to develop the skills found most useful in industrial R and D. For radioastronomy at least, there is evidence that, as it has grown into a Big Science, some of the more technical aspects of research (like building receivers and processing observational data) – tasks formerly carried out by students and scientists – have been gradually handed over to permanent technical staff. The trend towards larger research teams, with a more specialised division of labour, has aggravated the problem, in that students may no longer be able to take part in all aspects of experimental work. Furthermore, the development of radioastronomy into a Big Science seems to be associated with an increased tendency to purchase equipment 'off the shelf', as opposed to research staff building it themselves. In other words the growth of a Big Science would appear to involve certain diseconomies of scale.

If these trends continue unchecked, there is a very real danger that students will no longer have the opportunity to develop the skills that their predecessors have found so useful in their subsequent employment. In that eventuality, radioastronomy and Big Science in general, while they may still be funded relatively generously because of the contributions they make to our knowledge of the universe, will lose one of the most powerful justifications for their claims to a large fraction of the resources for scientific research.

Further reading

Barrett A H and Myers P C 1975 'Microwave thermography' *Bibl. Radiol.* **6** 45–56

Barrett A H *et al* 1981 'Microwave thermography applied to the detection of breast cancer' *Am. J. Roentgenol.* (to be published)

ESA 1978 *Economic Benefits of ESA Contracts* ESA/C (78) 104

Evans M K 1976 *The Economic Impact of NASA R and D Funding* NASA CR 144351

Irvine J and Martin B R 1980 'The economic effects of Big Science: the case of radioastronomy' *Proc. Int. Colloquium on Economic Effects of Space and Other Advanced Technologies, Strasbourg, 28–30 April 1980* ESA SP-151 September 1980

Martin B R and Irvine J 1981 'Assessing basic research: some partial indicators of scientific progress in radioastronomy' *Research Policy* (to be published)

Pavitt K (ed) 1980 *Technical Innovation and British Economic Performance* (London: Macmillan)

Ryle M R, Kurti N and Boyd R L G 1971 *Search and Research* (London: Mullard)

Schmied H 1977 'A study of economic utility from CERN contracts' *IEEE Trans. Eng. Management* **EM-24** 125–38

Shils E (ed) 1968 *Criteria for Scientific Development* (Cambridge, Mass.: MIT Press)

Weinberg A M 1963 'Criteria for scientific choice' *Minerva* **1** 159–71

Meetings and courses

Laboratory health and safety
25–28 October, Loughborough University, UK
Info: Centre for Extension Studies, Loughborough University, Loughborough, Leics. LE11 3TU

28th national symposium of the American Vacuum Society
2–7 November, Anaheim, California, USA
Info: Nancy Hammond, American Vacuum Society, 335 East 45th Street, New York, NY 10017, USA

International conference on fast reactor fuel cycles
9–12 November, London, UK
Info: The Secretariat, British Nuclear Energy Society, Institution of Civil Engineers, 1–7 Great George Street, Westminster, London SW1P 3AA, UK

SPSE 4th international conference on electrophotography
16–18 November, Washington DC, USA
Info: Society of Photographic Scientists and Engineers, 7003 Kilworth Lane, Springfield, VA 22151, USA

EEC conference on the information society
18–20 November, Dublin, Ireland
Info: Conference Office, National Board for Science and Technology, Shelbourne House, Shelbourne Road, Ballsbridge, Dublin 4, Ireland