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INVITED REVIEWS

"Small Equipment Strategy" in the Development of Astronomy

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Abstract Astronomy is an observational science. This paper points out that in the development of astronomy, the means of observation at every stage has as its main body the *large equipment* of the time, but equally important is the simultaneous development of *small equipment* as strategic complement. A number of historical examples are cited. The recently suggested "Special Radio Telescope Dedicated to Pulsar Research" originates in the small equipment strategy, and a brief introduction to this instrument is included here.

Key words: instrumentation — telescopes

1 ON THE "LARGE EQUIPMENT" OF ASTRONOMY

In the development of astronomy, the raising of the light-gathering power and other capabilities of telescopes is an ever-pressing task.

Astronomy is an observational science. Here, the word "observational" connotes both "detection" and "measurement" at great distances, and their target is the electromagnetic waves emitted by celestial bodies. The first task of the telescope is to see such electromagnetic waves. Only after seeing can we proceed to measure, and only after measuring can we begin to research. Therefore the capability of seeing comes first of all.

The larger we make the telescope, the greater is its light-gathering power, and we are enabled to see regions previously unseen. But the unseen region in the astronomical world is just enormous. Take a well-known example, we have reason to believe that the Milky Way galaxy contains hundreds of millions of planetary systems, but of these systems only one is known so far: namely, our solar system. Following the efforts of generations of astronomers we are beginning in recent years to detect the existence of giant planets around several stars. But if we wish to make effective measurements of earth-size planets outside our solar system, then we have at least to wait for the advent of the next generation of space telescopes. Of course, even that will only still be a very tiny step in the study of the numerous extra-solar planetary systems. And this is not an isolated example; in fact, celestial bodies in cosmic space are numberless, and we have observed only the tiniest proportion of the brightest. Our experience is that increasing the existing telescopic power a hundred-fold, or even a thousand-fold would not be excessive for the accumulation of fainter samples and finer details, for the opening-up of wider fields, or for the search for more and newer opportunities, whether on the level of planets, stars, or galaxies. On the contrary, as soon as the demands and expectations of a given epoch are satisfied by our endeavour, "the boat will be raised by the flood water", there will immediately appear new scientific demands, posing fresh challenges of a higher order.

This shows that so-called "large equipment" is updated from one generation to the next: at a given time, "large" and "small" are relative terms. To the astronomer, a telescope mounted on two axes with an aperture limited only by the technical or economical resource of the time, to him the telescope will be considered as large. At the beginning of the 20th century the largest telescope in the world had an aperture of about 1 metre. In the mid-century years, only an aperture of the order of 4 metres could be called large. By the end of the century, the aperture of a large telescope had reached the order of 10 metres. As we move into the new century, the so-called 30-metre class mosaic mirror telescope is being designed. This, for the present, can be said to have reached the limit of contemporary technology, anything larger would mean too big an investment and too long a construction time. However, we can be sure, after 10 or 20 years, 30-metre class telescopes will be overtaken in their turn.

The large telescopes of the world are getting ever larger, and their manufacture is also getting ever speedier. It seems there are two main constraining factors: technical resource and financial support, but note science's demand is not one. This is because, as said before, from past history down to foreseeable future, it is the capability of the large equipment that constrains the frontline research of the whole of astronomy, and not vice versa.

This state of imbalance between demand and supply exists equally in the study of the various fields of the astronomical world,—the stars, the galaxies, the small bodies within the solar system, and so on.

The above example specifically mentions optical telescopes, but the same description applies to instruments designed for working in other parts of the electromagnetic spectrum (radio, infrared, ultraviolet, X-ray, γ-ray). (And applies also to neutrinos, cosmic rays, gravitational waves.)

Because of the foregoing reasons, astronomers at all times, no matter how large the instrument they possess is, always regard as an ever-pressing task the research into instruments with greater light-gathering power and greater versatility. This has resulted in the continual updating of modern large astronomical equipment from one generation to the next.

But large equipment entails high cost and has its own limitations.

The high cost of large equipment means that, as far as possible, it is made suitable for all types of astronomical objects, for all kinds of investigation; in practice it comes down to picking out the most deserving from a host of applications for its use. These two premises in capability and observing time are intrinsic limitations of the large equipment. Therefore, the continually improving large equipment, though occupying an important position in the strategic disposition, cannot, when the whole situation is considered, exist and develop in isolation: we must, at the same time, pay attention to the strategy and functioning of other types of equipment, particularly the "small equipment" discussed below.

2 ON "SMALL EQUIPMENT" AND "SMALL EQUIPMENT STRATEGY"

2.1 Characteristics of Large and Small Equipment in Astronomy

The characteristics of large equipment in astronomy can be summarised under the following headings.

(1) Its power, particularly its light-gathering power, far exceeds available telescopes of the same type.

(2) Therefore it needs advanced and difficult technology, a relatively long research and development time, and a high manufacturing cost.

(3) Therefore it should be multi-functional and, as far as possible, be suitable for all types of frontline topics on all levels of astronomical targets.

(4) Therefore the number of applications to use the equipment will always far exceed the number of tasks it can undertake. This means that in the allocation of telescope time, the time support for a given project is often limited to a very small time slot.

(5) For the same reason, the various functions of the equipment must cater for a great variety of topics, hence the equipment's design is basically fixed. This means that the designing of the project for study is basically "equipment-led".

What we call "small equipment" is defined by the strategy of astronomical measurement, its characteristics complement the "large equipment"; relative to the latter, these are

(1) The equipment is relatively "small".

(2) The cost is low, the R/D time is short (if an existing telescope is used, then the R/D time is limited to ancillary instrumentation, and will be shorter still).

(3) The designing of the project of study is now "subject-led", that is, the project is designed around the subject.

(4) Therefore, it is basically a single-function instrument (or a small – number – function – instrument).

(5) Hence its time support for an individual project can be relatively long.

Thus, in the development of astronomical measurement, large equipment is, in army terms, the main force, while small equipment can be likened to the irregulars, the flanks and the rear support. The relation between the two is one of strategic complementation.

2.2 Three types of "Small Equipment"

Small equipment can be roughly classified into three types. We shall illustrate each by some examples.

2.2.1 Type One Specially dedicated small equipment, designed in answer to a specific need

The most famous example is the small radio telescope specially designed by Princeton scientists in the 1960s, in response to the theoretical prediction of the cosmic microwave background. They knew, of course, that for measuring the background radiation only a very small radio telescope was needed, they also knew that for measuring the cosmic background, one must be able to measure radiation at temperatures near absolute zero and that the instrument had to be very stable. Of course, unlike Penzias and Wilson, they did not realise that the horn paraboloid then lying idle in Bell Laboratories was precisely such a "weapon" (Penzias and Wilson knew the properties of this instrument but they did not have any knowledge of cosmic background radiation). Eventually it was the combination of the two teams that resulted in one of the greatest discoveries in astronomy. Looking back, the use of the horn paraboloid was not only functionally suitable, it was also the most economical (free of any investment in instrumentation), and still more important, it gained time where telescope time was at a premium. Penzias and Wilson made a lasting contribution in that, more acutely than anybody else, they realised the significance of small equipment and knew how to search for it, re-invent it and use it.

It was in the same decade, the 1960s, that the discovery of pulsars was made using a specially dedicated small instrument. This time it was a metre-wave radio telescope with a high speed recording capability that cost only 20 000 pounds sterling. So high a recording speed was then unknown (therefore it was also a "new weapon"). Although it discovered pulsars only by serendipity, now that it exists, the discovery of pulsars will be a matter of course.

Both instances are cases of "hitting the mark by a fluke". But in both cases, timely new weapons were made out of some small instruments that led to Nobel prize-class achievements.

2.2.2 Type Two Using existing large, medium, or even small equipment to complete different size projects that cannot be covered by the large equipment alone

Another Nobel Prize winning feat in astronomy—using pulsar timing to measure and detect the effect of gravitational waves—was achieved through a long-term monitoring with a large telescope—the 200-metre effective aperture Arecibo telescope, that did not belong to large equipment. This work can be said to represent the best use of this type of telescopes, telescopes that once functioned as large equipment but no longer rank as such. These can now take up tasks for which the present large equipment cannot spare the time or is not suited, and tailor themselves accordingly. Then, from the point of view of the project, although it has to forgo the high capability of the current large equipment, it now enjoys the freedom of being subject-led. Typical projects such as those requiring long-term monitoring (pulsars, variable stars, etc), or those requiring measurement of large samples (sky survey of galaxies, etc.), or those requiring large-scale identification and search (identification of X-ray sources, etc.), and so on, all can very naturally find matching instruments. Since such equipment does not require new construction and allows long observing time, it is essentially "non-large equipment", or, following our definition, may be termed relatively small equipment. (Of course, in practice we do not exclude the possibility of truly medium-size or even small, equipment taking up certain large-scale tasks.)

2.2.3 Type Three Studies on Increasing the Telescope's Light-Gathering Area and Small-Scale Experiments

The topic here can be divided into two strands according to content, one is the study of the structure and designing of the telescope itself and its composite system, researching into its "optical" (used here generically for any electromagnetic waves) properties including its light-gathering power, resolving power, size of field, imaging quality, and so on. The other is the continual acquisition of relevant items from rapidly developing technologies, first of all, from the technologies of various types of detectors, of computer hardware and software, and of different precision measuring and counting devices.

Issues of the second type are closely connected to the development of contemporary technology and high-tec production, often manifested in certain expectations of the product, for example, the present expectation for low-cost, high-sensitivity, large-area pixel detecting devices. These will not be discussed here.

We shall concentrate instead on the first type of concern, that is, the telescope itself and its composite system. For astronomers, this is a subject of unremitting effort from generation to generation. Here also included is the prototype manufacture, or trial runs, of the large equipment of the time.

Under impact from advancing technology, this field experienced several important breakthroughs during the 20th century. Apart from the constant maturing, during the early years, of the techniques of glass casting, glass polishing and optical surface treatment, no breakthrough in the first-half of the century is more important than the invention of the Schmidt telescope in the 30s. It not only marks the beginning of large-field telescopes, it marks also an important development in multi-element (two-element) light-gathering systems.

In the second half of the 20th century, technical advances accelerated and new breakthroughs duly materialised. Before, the radio telescope simply could not compare with the optical telescope with regard to either collecting area, resolving power, imaging quality or field size, but the construction of the aperture synthesis radio telescope in the 60s and its successful first measurement changed the whole situation overnight. As general principle this instrument demonstrated that synthesis of multiple unit telescopes can result in a large collecting area and high resolution imaging. This undoubtedly is a tremendous breakthrough.

It was during the same period that the concept of homology was first used in the designing of radio telescopes, which in fact kicked-started the first trial of active optics. This conceptual breakthrough, together with aperture synthesis injected new optimising factors into the framework of large equipment for the radio range. In the optical range, there appeared separately such large-scale designing as multi-element active optics mosaic thin mirrors, and experiments on optical aperture synthesis carried out with perseverance over many years.

Of course, the greatest breakthrough during this period must still be the advent of space astronomy. Space instruments for different electromagnetic wave ranges—the Space Telescope" and Space Observatory", developed from small scale experiments, some of which amounting to contemporary large equipment, all ranked first in terms of investment on single items.

These achievements all originated in combination of the fruits of contemporary advances in technology and the creativity of researchers in astronomical instrumentation. As global economy and technology continue to develop, this trend will be kept up.

3 STRATEGIC THOUGHTS ON CONTEMPORARY SMALL EQUIPMENT

We shall discuss separately the three types proposed in Section 3.1.

3.1 Type One – Special Dedicated, Subject-Led Equipment

Here the emphasis is on "subject-led". Of the utmost importance is the joining together of the instrument and science studies in formulating the proposal and designing the plan of measurement. Researchers from the two sides should reach such implicit mutual understanding as exists between the two partners in a doubles ball game. The Boomerang and Maxima experiments in 2000 using balloon-borne microwave telescopes to measure the spectrum of the cosmic microwave background radiation with huge success are the most striking example in the recent past. In astronomy whether at the level of planetary systems, or stars, or galaxies, right up to the cosmological level, there exist to varying degrees large numbers of such topics, and it is only through the mutual collisions at the deepest level, among all three—technology, observation and theory—that intellectual sparks are produced. Such sparkling signifies creative, unfettered development. (This is probably the reason why most of the Nobel Prize astronomical observational projects so far originate in this kind of subject-led equipment.)

3.2 Type Two – Non-Large Equipment Specially Used for Frontline Tasks that are Unsuitable for the Current Large Equipment

Here the emphasis is on frontline targets that cannot be covered by large equipment. Projects (or lines of research) of the large sampling, long-term monitoring or wide searching types particularly have to be realised by mobilising the large number of facilities of the non-large equipment class. At the present time when internet linking and digital techniques continue making rapid progress, when projects involving joint operation and shared results freely appear, we need comprehensive viewpoints and insights on the current development of astronomical science to gain initiative and reap maximum scientific benefit. Here, the teaming-up of resources theoretical, observational and technical is again of paramount importance.

According to the situations in the two foregoing types, close interchange of ideas and cooperation between theoretical, observational and technical researchers is indispensable for realising the small equipment strategy characterised by the term "subject-led".

3.3 Type Three – Small Equipment used in Basic Original Research on Telescopes

Here the main content can be said to be the pre-study that is ever aiming at the next generation of large equipment. This study is closely connected to the forefront of technical development of the time. Of the present relevant technologies the most influential include the making of more intelligent control systems and the rapid development in the collection and treatment of huge volumes of information. These have led to, (1) the philosophy of telescope designing leaning towards breaking the whole into parts, towards interactive multiple components, $\cdots$. Already at the present stage of progress we have many successful instances from mirror mosaic to aperture synthesis. Further development will be their faster and larger-scale applications thanks to continuing advances in techniques and methods; (2) the capabilities of telescopes will continue to be favourable for the opening-up of the field of huge volumes of real time information gathering and high time resolution. This opening-up has already been underlined by the present application of optical fibre in astronomical observations and the continuing advances in high sensitivity detectors. Using the language of the Appendix of this paper, what we call "high new technologies" belong to the most rapidly developing portion of the whole society's "observing tools store" ("technical methods store"). As stated in the Appendix, research on the astronomical telescope belongs to research in technical science. To carry out research, scientific workers at all times select from the store of the whole society whatever observing tools (technical methods) they need to create the new technologies and new methods they need. Of course, the tools are not confined to the those mentioned in (1) and (2) above, but the new development that those generated out of existing tools (techniques), has appeared wave upon wave, each better than the last, and this trend is still growing.

When we consider the present strategy of astronomical observation, the following aspects merit investigation.

3.3.1 Point One

Freed from the effects of the earth's atmosphere, space observation undoubtedly has an absolute superiority over ground observation. However, in the foreseeable future, even when a Moon-based observatory is operative, ground facilities in the optical and radio waves allowed in by the two atmospheric windows, because of economical and technical reasons, will still have their own place. Talking only of large equipment, ground-based instruments have the advantage of being able of developing in the direction of "large", this is manifested in their actual size scale far exceeding the limit of capability of space equipment of the same type. The work sharing between the Keck Telescope Array and the Hubble Sky Telescope at the end of the last century has given a rough proof of this proposition; for the "Square Kilometre Array" in radio astronomy, there is up to now no conceivable space means that can match it.

Hence, from a longer strategic perspective, we must embark without delay on an investigation of the resource of optical and radio ground observing sites with good weather conditions, free of man-made interference and with scope for expansion. And timely preparatory studies should be made on such related topics as remote control of telescope system and safety measures against catastrophic climatic changes. (Such measures are necessary, because the site may very possibly fall in some virgin land on some remote plateau, not excluding a certain location in the Qinghai-Tibet plateau.)

As a basic type study, wide band connection between telescope units is an important topic in the development towards "large". It should be constantly pursued at the wake of technical advances.

3.3.2 Point Two

A basic problem in astronomical observation is the distance in recording capability between integrated light and dispersed spectrum. For the same astronomical target, we need a much larger telescope or a much longer integration time to make spectral measurement. In principle this is the situation at any wavelength, but for the present (and perhaps for the next few decades) our greatest concern is still with the visible together with its ultraviolet and infrared extensions. For this range, the introduction of "multi-fiber technique" has ensured long-stride advances in the capability of large telescopes of making simultaneous spectral measurement of multiple targets. Using large telescopes to obtain large volumes of spectra of various types of objects is expected to be a very important resource in the next phase of astronomical development.

An important trend in to-day's astronomical development, namely, the rapid growth in the number of targets and volume of information will, from the list of further observing priorities, pick out precision measurement of selected large samples, such as the precision measurement of certain type targets in the optical, radio, X-ray, $\cdots$. Batch spectral observation belongs to this class of selective large sample sky surveys. Hence, whether we can simultaneously sample large fields for a large number targets of some selected type directly impinges on the result of our undertaking. Thus viewed, increasing the light-collecting area of a "LAMOST type" telescope is an undertaking well worth considering. Imagine we increase the aperture of LAMOST to 10 metres, hence its total length to 100 metres, and we set it up on top of one of the mountains of the world with good seeing (or on one in China after a detailed investigation of our own site resources): it will occupy an important position among the "large equipment" of the next generation.

Continual increase in the field size of the LAMOST mosaic Schmidt telescope and in its imaging quality should be considered as one direction of our long-term endeavour.

3.3.3 Point Three

For a long-term view, imagine we set up an optical telescope array on the Moon, or on some site of decidedly superior quality, then we should include in our consideration three types of "large equipment":

One type is large-size, large-field Schmidt telescope, to be used in multi-colour deep sky surveys. The aim here is large-scale improvement in both the quantity and quality of sky surveys to enrich the basic resource of astronomical research. The second type is large-size, multi-fiber spectral Schmidt telescope, to be used in collecting huge volumes of spectral data. The third type is large-size telescope array: when used in isolation, one of its units can make precision measurements (including high-resolution spectral measurements) on selected targets; when the whole array is used as one synthesized aperture, then it can detect the faintest and the finest detail within each of the various types of targets. (For example, an optical synthesized aperture of baseline 1000 metres has a resolution of 0.1 mas. For a perspective, if we place the Sun at the position of the nearest star, then the Sun's diameter will be about 7 mas and the structure of sunspot groups on the sun's surface will be clearly resolved. At this distance, the orbital radii of Venus and Earth will be, respectively, 600 and 800 mas, easily separated by the side of the Sun; at least six of the planets of the solar system will have magnitudes around 24, their positions and movements in their orbits will be visible, $\cdots$. We can imagine it entirely possible that such a large equipment can isolate many more distance planetary systems.)

The above analysis shows that for the astronomical telescope (or astronomical instruments) as a technical science, basic research is very important. We need to take into consideration the overall situation and prospect of the science. Take a recent example: over the years gone by Chinese researchers on astronomical instrumentation invested much of their energy in the reflecting Schmidt telescope and in active optics, and this has turned out to be a move of great foresight.

4 ON THE SPECIAL PULSAR-DEDICATED RADIO TELESCOPE

This is a recent proposal made to the Chinese Academy of Sciences. A brief explanation is contained in an internal circularised report entitled "Construction of a 50-metre Special Pulsar Radio Telescope for a Multi-Disciplinary Development of Pulsar Timing". As it is relevant to the small equipment strategy we shall present here a brief introduction of this telescope.

With their extraordinary physical properties and extremely stable periods of pulsation, the pulsars have opened up many fields in astronomy, astrophysics, physics and time measurement. Since the 1970s when astrophysics became included in the Nobel Prize for Physics, there has been a total of seven such awards, of which two concerned pulsars.

Pulsars are difficult to discover, and right up to the present, at the very forefront of development are sky survey projects designed for the discovery of pulsars, carrying expectations of new breakthroughs, and always injecting vigour and vitality into pulsar research. In another direction, even for the modest number of pulsars that have been or are being discovered, the necessary "follow-up" observation has already lagged far behind. This is because the most basic "follow-up" is frequent monitoring over long periods of time, but the telescopes of the world that are suitable for observing pulsars are already overloaded with large numbers of radio astronomy projects of different types, and can hardly satisfy the time demands of pulsar monitoring. The efficiency of pulsar monitoring has thus become a key issue in the development of this field.

These circumstances mean that pulsar study has more than usual scope for exploitation. Under this circumstance, although we started late in this field there is, relatively speaking, still room for development. At the same time, large-scale increase in the monitoring efficiency is an unsolved and yet solvable problem, equally for all teams, irrespective of strength. For us with limited resource a direct attempt at taking up this challenge is an opportunity. If we grasp this opportunity and resolve ourselves to taking a lead in the construction of a specially dedicated telescope for the main purpose of pulsar monitoring, then we shall gain certain advantage in today's pulsar study. The situation in this field in recent years, particularly the development in the techniques of pulsar monitoring, lends impact and urgency to the above view. The report cited above, while focusing on the development of the measurement of pulse arrival time of millisecond pulsars, underlines the simultaneous development of three important fields, detection of cosmic gravitational waves, pulsar monitoring and experiments on basic time standards. The report sets out the strategy of using a 50-metre pulsar-dedicated radio telescope and multi-star measurement to make inroads into these areas and discusses the question of practicability of this strategy and means of its realisation. The report points out how, over the 10-plus years from the discovery of millisecond pulsars in the early eighties to the mid-nineties, this work was successfully initiated, its techniques successfully passed scientific tests and matured, and its scientific significance clarified. The scientific achievements are remarkable, including: (1) the long-term stability of pulsar timing measurement has reached 10^{-15}, comparable to the present day atomic time standard; (2) an upper limit of 10^{-8} of the closure density of the universe has been determined for the gravitational waves in the initial cosmic background. This upper limit places a strong constraint on the model of cosmic strings in cosmology.

During this stage the timing measurement was carried out using individual millisecond pulsars. The greatest achievement has come from the Princeton University team, who used the Aricebo radio telescope to carry out regular, single-star measurement over a long period of time. Form the start, through maturation till preliminary development, their results obtained reached the very forefront in this field, and can also be considered as having reached the limit of single-star method. The main restricting factor is this: there are several minute yet very important parameters that are dependent on the direction of the pulsar to the observer. Therefore, further development must go beyond the limitations of single-star measurement, must make "multi-star" measurement on targets suitably distributed in different areas of the sky. Our specific proposal is: 1) from millisecond pulsars of the largest fluxes we select 15 or so to be the targets of multi-star measurements; 2) the selected stars should be, as far as possible, uniformly distributed over different directions of the sky; 3) each of the targets should be measured as often as possible (e.g., once every day, each time 1–2 hours); 4) this measurement should be kept going over years and years.

The receiver technology required for doing this job has already been solved abroad, which we can import wholesale. The focus of the problem is the antenna. The fluxes of millisecond pulsars are weak, and so an antenna with a large aperture is required. The Aricebo telescope is one of such large antennas in the world, but it fields is too small. The other antennas are overloaded with projects and have so far been used only very sparingly on pulsar timing.

It is our belief that constructing a radio telescope specially dedicated for pulsar timing is, for us, an optimal choice (maybe eventually proven to be the only choice). By so doing, not only do we ensure that we shall satisfy the need for a highly specialised and rather laborious work, but also, we can "cut the garment according to the figure" (synonymous with "subject-led"), and make the most reasonable choices. The main choices are: 1) since the wavelength currently used for pulsar monitoring can not be shorter than 20 cm, the reflecting surface of the antenna can be limited for working at 20 cm, and the tolerance can be allowed to go up to 1 mm; 2) for long-term monitoring we can choose the "brightest" pulsars, which means we can limit the diameter of the antenna's reflecting surface to (not greater than) 50 metres. Then we can omit from the requirements on the construction of the antenna all "higher" functions that go beyond what are required for the planned task of pulsar timing. By identifying what we do do and what we do not do, we shall realise a practical and economical instrument, and because it is relatively simple, its construction time could be fairly short. In our proposed plan the antenna aperture is fixed at 50 metres, the cost at 8 million yuan (should some unforeseen circumstances arise, the total investment should still not exceed 10 million yuan).

APPENDIX ⋆

THE POSITION OF OBSERVING EQUIPMENT IN THE DEVELOPMENT OF ASTRONOMY

First let us use a block diagram to express the research process of an astronomical observing programme (see Fig. 1).

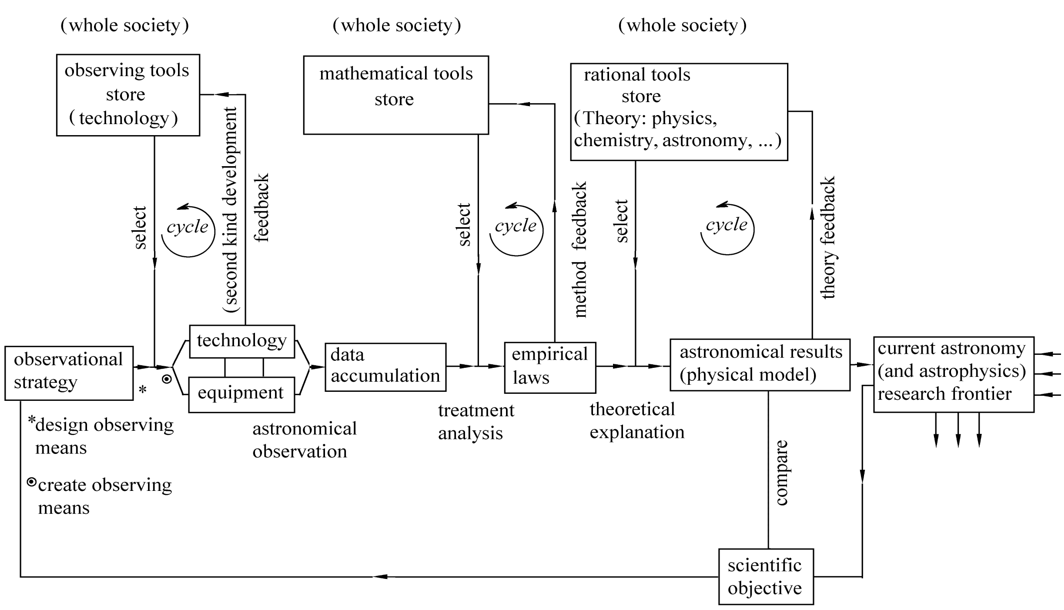

Fig. 1 Astronomical observational study block diagram.

This block diagram is equally suited to describe the development of the astronomical science. In the diagram, "tools" is a general term, representing mainly the corresponding "knowledge", for example, "observing tools" refer to the knowledge of the various kinds of technology, material and applications possessed by the society at the present time. The researcher formulates his observing strategy according to his scientific objective, selects from the "society's store" the right "observing tools", designs and creates the observing means aimed at the scientific

⋆ Although the content of this Appendix does not directly concern "small equipment", it is applicable to all astronomical equipment.

objective, including observing equipment and their method of application; the equipment, after being applied, is tested by the actual observation, and progress will made through mutual feedback between the two. The diagram shows the organic re-cycling: observing strategy → observing equipment → astronomical observation → astronomical target of study. From the point of view of the observing equipment, what goes before it in the diagram are its causes, what after, its consequences: thus is indicated its position in the whole process. The diagram also shows how the whole process is linked at various points to the "science/technology store of the whole society" through mutual feedback of benign cycles.

We now proceed to elucidate the particular example of such re-cycling and interaction in technical methods in the upper left part of the diagram.

As said before, the term "observing tools" in the diagram implies that we regard the knowledge of techniques and methods as a tool possessed by the whole society, and that we regard the knowledge of techniques and applications possessed by the whole society as a resource (the resources of relevant information and material are implicitly included). Because knowledge is not diminished by use, such a resource is inexhaustible. So we can regard such a resource as a "store" of observing tools. As technology continues its advances, the storage of this store is increased all the time. Obviously, this intellectual storage has people as its carrier. Its degree of richness and rate of growth are a measure of the technical capability of the whole society (on the surface it is technology, but in essence the function of science is all important). The usage of the store, on the other hand, is a reflection of the level of science and technology management.

For convenience of explanation, we shall, for the time being, refer to this "Society's Tools Store" with knowledge as its basic element and people as its carrier, simply as "technological resource" (and similarly, "theoretical resource"); applying the technology resource to production (or other practical applications) to generate product is what is generally known as "development (in the sense of R&D)". When the technological resource is used in scientific studies, then the product is new techniques, that is, new technological resource. We liken this phenomenon to development, and call it "second kind development". The second kind development occupies an important position in the development of high-new technology. Now, if the technological resource is used in a natural science study, in particular, in an astronomical observational study, then the process will consist of two steps, as shown in the diagram above: the first step is technical innovations around the equipment and its application, the second step is the application of the equipment so generated to the astronomical observation. The first step here actually belongs to technical science study (or more precisely, to the study of the particular technical science of astronomical instruments), and shows up equally as a second kind development and creation of new technological resource. (The "cycle" and "feedback" in the diagram express this effect). The greater the challenge of the forefront project of astronomical study is, the greater is the challenge of the requirements on the observing means, and a correspondingly high level of second kind development will result. That is to say, the feedback to the society's technological resource usually has a very high, high-new technology content. The second kind development is an important contribution by the natural sciences including astronomy to practical applications. Although it does not directly generate products, it creates technological resource "on the spot", and often high-new technology at that.