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SPACE SCIENCE BEYOND THE SOLAR SYSTEM *

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1. A Matter of Scale

All of the speakers who will appear at this rostrum will ask you 'to think big'. For space is big. I should not like to be quoted as belittling the achievements of space travel and space exploration. Yet I have to ask you to think 'even bigger'. It is all a matter of scale. Man has gone *only* as far as the Moon. The subject which the organizers have assigned to me is: everything beyond the planets out to the distant reaches of the Universe.

Let me try to refresh your appreciation of the enormous proportions in scale.

If the Moon is overhead and I would step on a folded newspaper in order to have a closer look at the Moon, you would think I had lost my wits; yet, to travel to the Moon in order to be closer to the stars or the Milky Way is futile in the same proportion. Other valid reasons for taking observations from the Moon *do* exist. For one thing, it is quiet from interference, especially at the back side. And the platform is far more stable than a space station.

Nothing can travel faster than light. Here are some typical light times: to the Moon 1.3 s, to the outer planets hours, to the stars years and centuries, to other galaxies millions and billions of years. Man's speed in low orbit around the Earth is one part in 40 000 of the velocity of light, or what is the same, nearly 1000 times faster than running at top speed. If we take this modest speed as typical, we have to multiply each of the mentioned light times by 40 000 to get an estimated human travel time. The title of my talk may, therefore, just as well be read as 'Space beyond flight'. This is all I shall say about space travel.

2. The Time Line of Man's Endeavour

Space science is a human endeavour. Let me, therefore, introduce a measure of time related to human life time. I take the unit of 30 years, which approximately equals 1 billion seconds or 1 billion heart beats. In the more affluent societies on this globe the time span of one human life is of the order of 2 to 3 of these units.

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Space Science Reviews **65:** 201–219, 1994.

I shall now review a bit of history in seven such steps of one gigabeat each. Brace yourself; developments really went fast!

1825. Steam engines are in full use in mining, traction and industry. But the basic theory of these engines is not yet understood. Carnot makes the first start with a science that will later be called thermodynamics.

1855. Conservation of energy, the 'first' law of thermodynamics, has been discovered, and scientists immediately raise the question where the Sun and the other stars get their energy from. Visual spectroscopy reveals that there are stars of many kinds.

1885. My father first goes to school, walking of course. Physics has become the domain of mathematical wizards like Gauss, Bessel, Rayleigh, but the major breakthroughs are yet to come. The Sun is understood to be an average star among many. But the guess that our Milky Way system may be one galaxy among many is still a bold speculation. The prize-winning 36-inch reflecting telescope, the biggest on Earth, is bought by Mr.Crossley and donated to the newly established Lick Observatory.

1915. A few years before I was born. Einstein's relativity theory had renovated physics. Quantum mechanics was like the steam engines of 90 years earlier: in practical use but not understood.

There was a lot of adventure in astronomy. The large new telescopes in California showed what nebulae and galaxies really looked like. Unsuccessful attempts to pick up radio waves from the Sun. Attempts to measure the different speed of light in different colours in interstellar space, equally unsuccessful but then hailed as a big discovery. A hot debate was raging whether or not the spiral nebulae actually were 'island universes', galaxies as we would say now.

The search for the source of 'atmospheric electricity' (i.e. ionization) by balloon flights had shown that the source was getting stronger when the balloon flew higher. Something must be coming from above. Dr Boorstin yesterday stressed the importance of a good terminology. I like the name, 'Cosmic Rays', coined a few years after the discovery, for this mysterious radiation. It was a double confession of ignorance: 'rays' meant it was something, we do not know what; and 'cosmic' meant that it comes from out there, we do not know from where.

1945. The war ended this year and the university was reopened. Miles away, I had seen the first rockets being launched, presumably with warheads destination London. My imagination was not bold enough to foresee that another billion heart beats later I would be actively helping to design instruments to be placed on such rockets for real astronomy!

One of the things I did around that time was to review the very little that was known about radio waves from space through the pioneer work of Jansky and Reber. This was a second window in the spectrum, besides the visual one, where the air was transparent to radiation from outer space. In order to explain this window concept in a colloquium talk, I felt it necessary to produce a chart of the entire spectrum, as others have done before and after. A simplified version is shown in

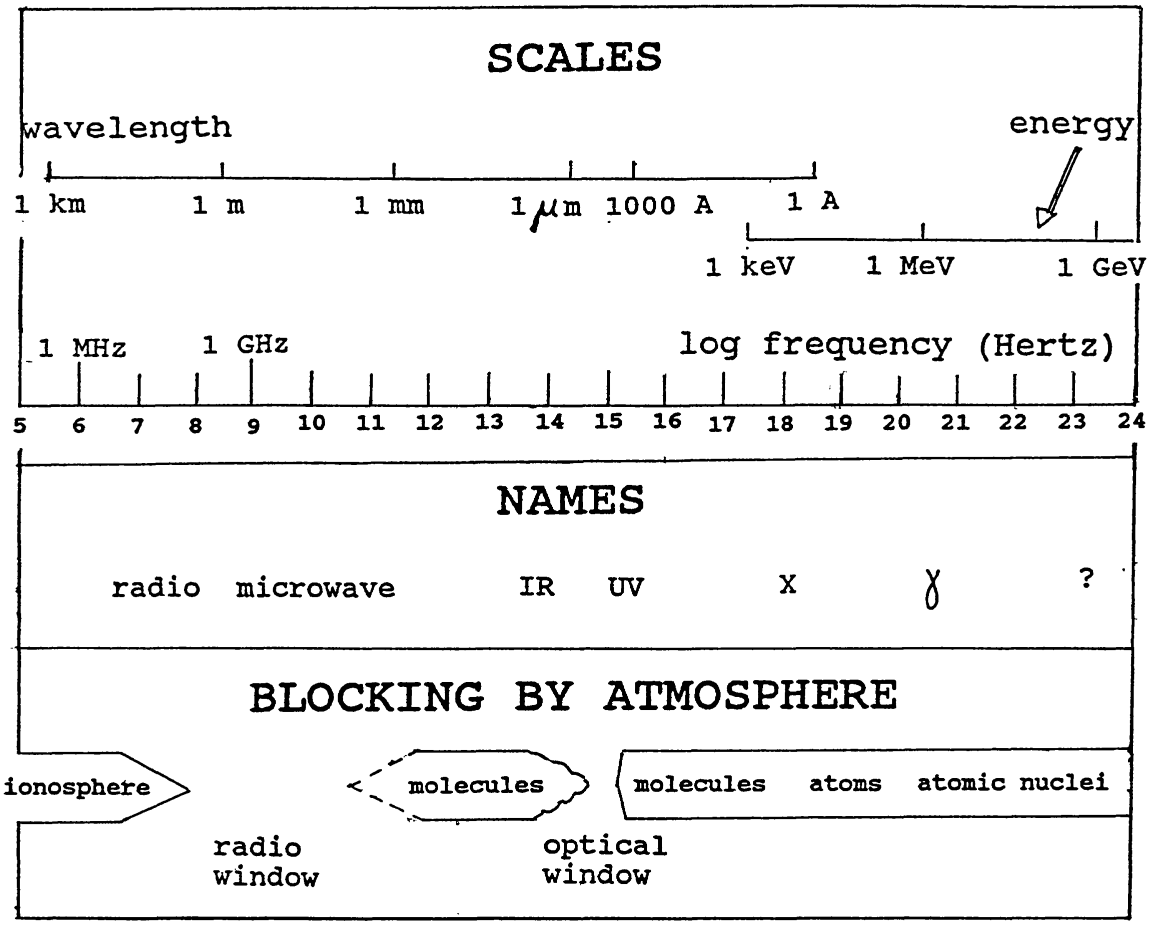

Fig. 1. The full astronomical spectrum and its visibility from the Earth. Adapted from chart shown in 1944.

Figure 1.

At the far end of the highly energetic radiation, at a billion electronvolts energy, beyond ultraviolet and X-rays, I was at a loss. By that time, the cosmic rays, from their dependence on the geomagnetic latitude, were known to be mostly ions, with protons in the lead. But was there also a cosmic high-energy component that would, like all electromagnetic radiation, travel in straight paths unaffected by the magnetic field? This was a vital question for astronomy. For if such rays could be detected and their direction established, they would reveal the position of their sources. I did not find an answer to this question in the libraries. So the chart had a question mark, at the position where we now proudly place gamma-ray astronomy.

1975. Developments continued at top speed in many fields in parallel. The spectacular advance in computers was as essential to our present achievements as the advances in rocket propulsion were. Owing to the computer, finding a needle in a haystack, which is a metaphor for finding 1 item in 10 million with a deviating signature, is not impossible but has become a routine operation in modern space science data analysis.

By 1975 the space age was well advanced. People had circled the Earth and

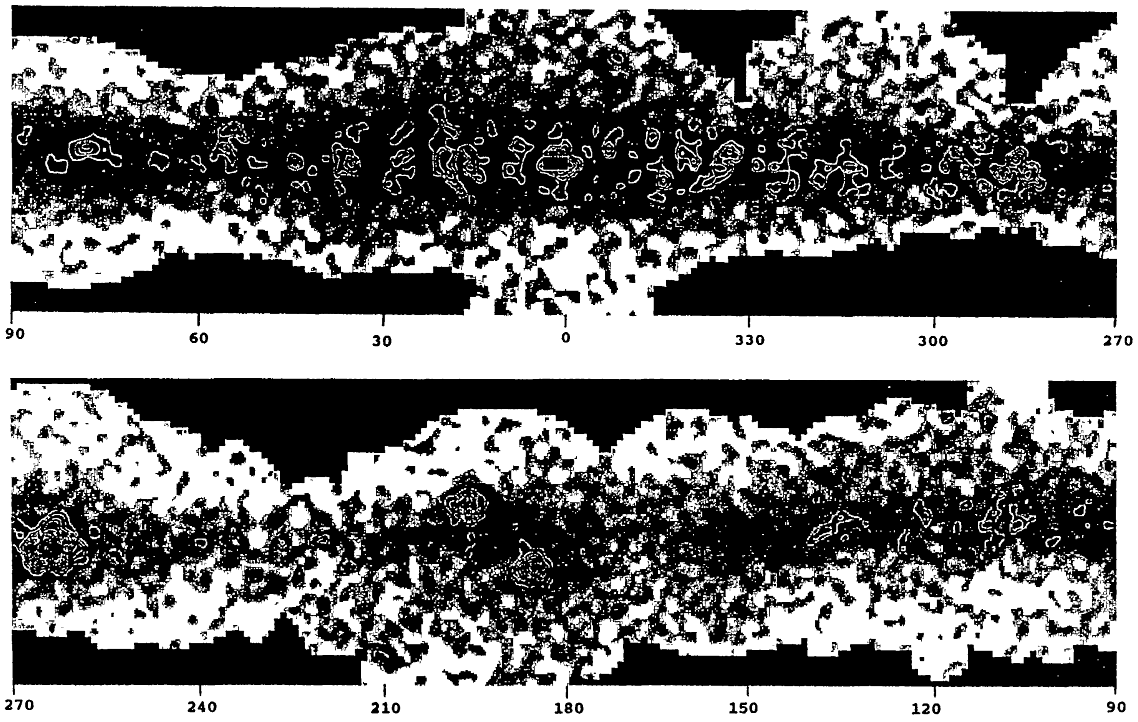

Fig. 2. The gamma-ray sky as mapped by the Cos-B satellite (1975–1982) along the entire galactic circle. Latitude range $b = -25^\circ$ to $+25^\circ$. *Top*: galactic centre and surroundings. *Bottom*: anti-centre directions with the strong sources Vela (at left) and Crab and Geminga (near centre). Part of the top map in a different representation forms the frontispiece to *Space Sci. Rev.* **49** 1988. (Courtesy J. B. G. M. Bloemen and W. Hermsen.

walked on the Moon. And – if you permit me some parochial statistics, counting the European Space Agency (ESA) alone – eight successful scientific satellites had been launched, three of which had as their major task the collection of scientific data on astronomical objects beyond our solar system. One of these, COS-B, launched in 1975, produced the first real map of the Milky Way (and of some outside sources) at gamma-ray energies. The question mark of 1945 had become a map.

The slide I most like to show at this point, is a close-up of the cake on which a German baker had copied that map in coloured candy when we celebrated 5 years COS-B in orbit. Good luck, for the design life time was only one year. Figure 2 shows a more informative version in black and white. I should also add that developments continue and that the EGRET instrument on the recently launched Compton Gamma-Ray Observatory (CGRO) is now producing similar maps with a higher precision.

2005. Unnoticed I have passed through the mysterious barrier called ‘now’.

This 30-year jump may feel like a bigger leap. But it is again just another billion heart beats. Is this a more eventful period? People’s feelings about this question seem to vary. For myself, in fair comparison with some of the other leaps I sketched, I would not call the present one more fruitful or more exciting or more heroic (a word used by one of the speakers yesterday). The one difference is that we are in it and may still do something about it.

In terms of planning, the entire period until 2005 is ‘now’. Planning, designing, funding and building a major space mission just takes that long. The present slot of the next 10 or 15 years is already well filled with excellent proposed or approved missions. I find this a healthy situation (but not everyone agrees!). The absence of such plans, which would reveal a lack of good ideas, would disturb me a great deal more.

Here are some examples of how long an actual project takes. My first documents about the rather modest infrared satellite IRAS date from 1971; it flew very successfully in 1983. Now, another 10 years later, research scientists in many countries are still working with its precious data. More recently, the Hubble Space Telescope was launched in 1990. Just about a billion heartbeats earlier, at the COSPAR meeting in Washington, 1962, I heard a truly distinguished evening lecture by Lyman Spitzer about these plans. For the major part of the intervening years I sat on a multitude of committees, boards, teams, councils and panels trying to help make it (the HST) happen. It happened alright and is now giving marvelous results.

2035. A lot might be said, and perhaps should be said, about this relatively near future, in spite of the fact that half the present audience won’t live to see that day. It is my conviction that studying the stars and the Universe will be as exciting then as it is today. But it will *not* be the driving factor for the decisions which the world will face at that age. So forgive me for ending this brief history lesson right here.

3. Completing the Spectrum

‘Completing’ something is not a high-ranking aim by itself. But it sounds attractive enough to be often advanced as a good reason for embarking on a project. A blank spot on the map of a continent calls for exploration, and so does a blank spot in the spectrum. Yet, it is wise to ask why we should. If the exploration just brings more of the same, it is not very important. In astronomy, my countryman Kapteyn initiated early this century the plan of selected areas, arguing that studying some areas of the starry sky at great depth would teach us more than a random exploration of the entire sky. Might we, in analogy, study only selected portions of the spectrum? The answer is *yes* for an object having a continuous spectrum. A dozen bands suffice, for instance, in checking if the intensity of such an object follows the curve of a certain temperature. These bands need not be narrow. Generations of astronomers have done well with the colour distinction between blue and yellow-green, that matches visual and photographic magnitudes. The wavelength ratio was 1.25, which is a tenth of a decade, or, as Figure 3 shows, in the musical analogue a third of an octave. Observing with such wide spectral bands is like playing the piano with your fists, hitting 4 keys at a time. Not very refined but still good science, for the full spectrum map is equivalent to a piano on which some 200 fists would fit side by side.

But nature only rarely shows objects with a thermal continuum spectrum. The tranquil settling to an equilibrium that can be labeled by a temperature is an

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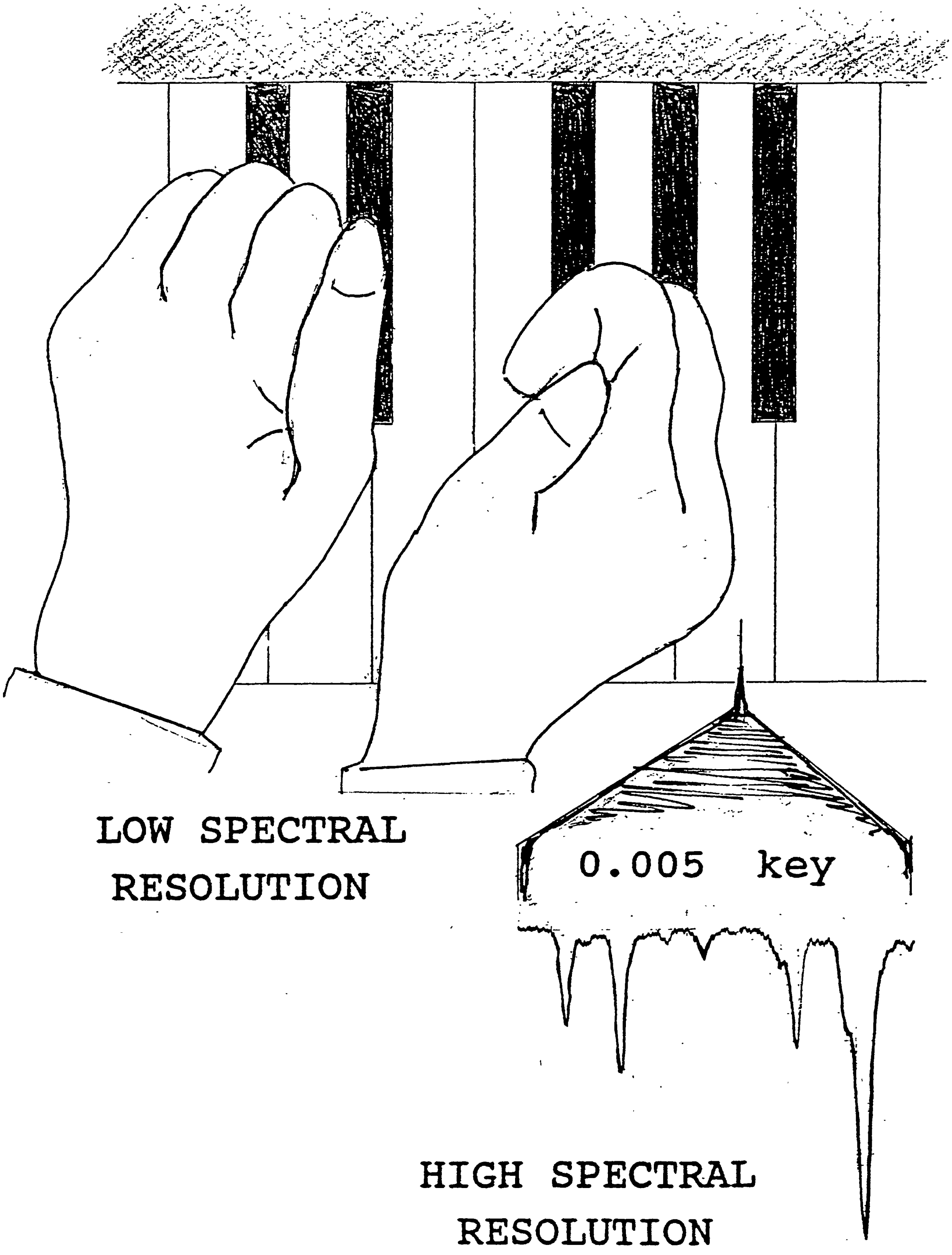

Fig. 3. Low and high resolution in astronomical spectroscopy, illustrated by their musical analogues.

exception rather than a rule. Violent events occur on all scales, leaving their marks in all areas of the spectrum: the formation and excitation of molecules in the infrared, atoms and ions in the ultraviolet and visible spectrum, reactions in the inner atomic

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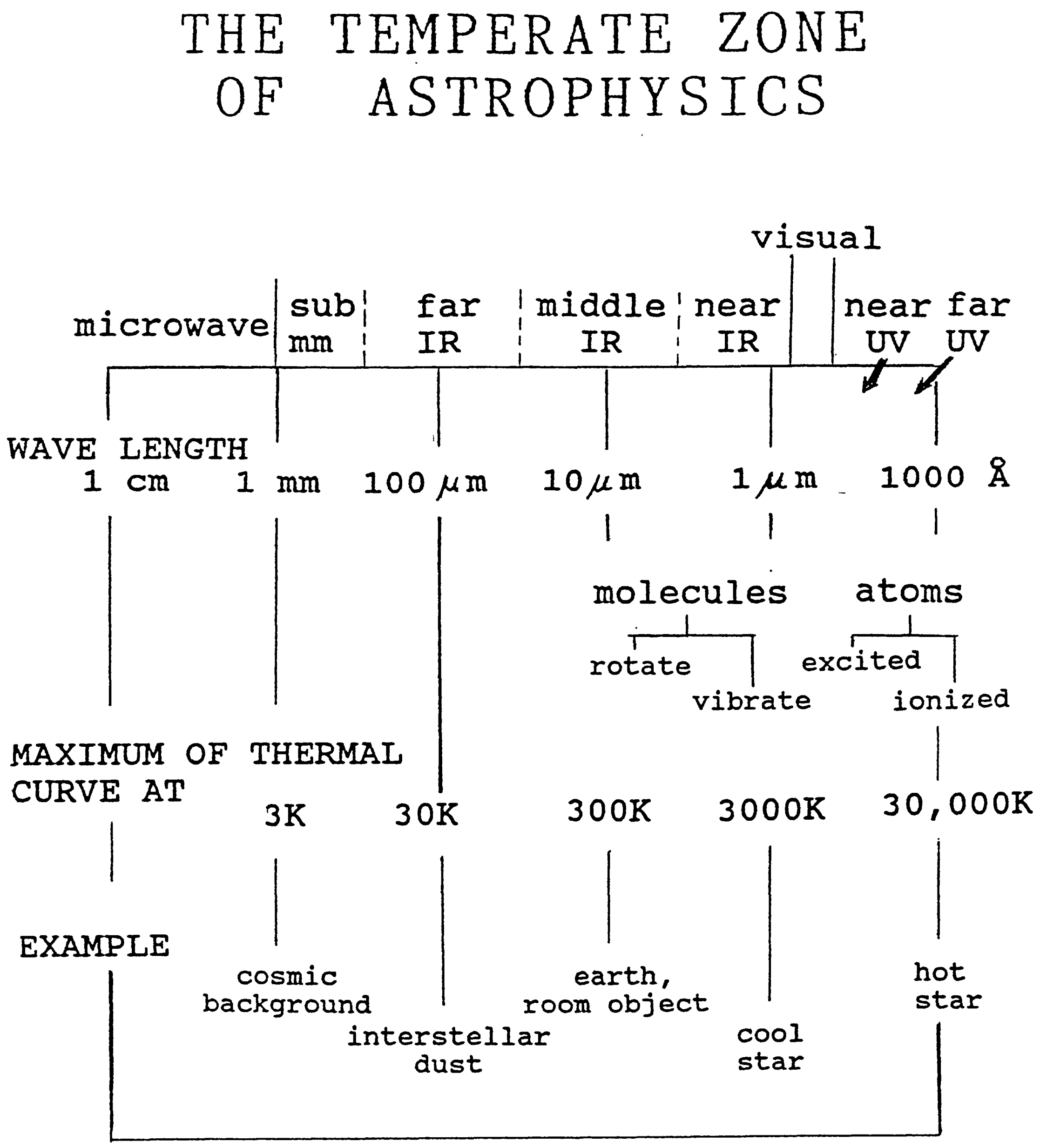

Fig. 4. Physical events and astronomical objects which set the pattern in the temperate zone of astrophysics.

shells in X-rays and on the scale of nuclei and elementary particles at gamma-ray energies. Some familiar ones are indicated in Figure 4, which shows the central five decades of the spectrum. I labeled this the 'temperate zone' of astrophysics, because the truly high and truly low frequencies have been suppressed. But what we humans experience as temperate is only one percent of the width of this slide. Read Shakespeare's sonnet: 'shall I compare thee to a summer day? Thou art more lovely and more temperate'.

Recording these signatures, telling them apart and understanding them, all requires good spectral resolution, and often very high resolution. The diversity of the visual spectra of normal stars was globally understood by 1930, but the subtle variations in their chemical composition became accessible for study only by high-resolution photometric spectra. The *Atlas of the Solar Spectrum* of 1939 forms a good landmark of this new age. In the same musical analogy, every 'key of the piano' was subdivided in this Atlas into 5000 subkeys; a sample from the atlas that covers one half percent of a piano key is shown as the inset of Figure 3. Similar studies on other bright stars soon followed and this development continues until today.

I worked on this precious, brandnew atlas as a student, but the reason for recalling it is not nostalgia. I need a reference to suggest where we stand with present-day X-ray astronomy. My assessment is that we are at the stage where stellar spectroscopy was around 1930. We have a good understanding of the main types of objects and of their continuous spectra. But we have only just started the study of spectral lines; many new discoveries may be in store. We are still near the beginning of our exploration!

What has been said about spectral resolution in the X-ray domain can be recounted with some variations in most other regions of the spectrum.

The desire to observe the fundamental ultraviolet lines of atoms and ions was the drive behind the Copernicus mission, which flew in 1972. It has, in a new form and for much fainter stars, been taken up again by the Hubble Space Telescope HST. The even farther ultraviolet, now commonly called extreme ultraviolet EUV, was once believed dull because space was expected to be mostly opaque by absorption in the interstellar gas. Fortunately, nature is more whimsical and EUV studies of objects in the solar neighborhood have turned out to be quite valuable.

Infrared astronomical spectroscopy has a lot to tell us. Short and long missions with the most ingenious cooled detectors have given one fascinating result after an other. They have been made with rockets and satellites, supplemented in the near infrared by groundbased and airborne instruments. The overall situation in space infrared astronomy appears to me that we have had plenty of appetizers but not yet a full meal. We need dedicated satellites for IR spectroscopy, the first one of which, ISO, is in the making for launch in 1995.

Luckily, many molecular emission lines do not need space instrumentation. They fall in the atmospheric radio window. Some 80 exotic molecules have been discovered by groundbased telescopes, a good part of them in the early seventies, when the art of building low-noise receivers had advanced to permitting measurements within one hundredth of a degree Kelvin.

In this quick overview of the astrophysical questions that may be addressed by observations in various domains of the spectrum, I have glossed over many points. These include the spectral and angular resolution desired, the speed of observation, the possibility of measuring polarization, and many more. Each of these specifications has to be carefully chosen with a view to the astrophysical problem that will be addressed. And each of these, in turn, may become a driver for the design (and the cost!) of the space mission.

A prime specification, and a recurring topic of long debates in the planning stage, is: how deep can we reach? What is the faintest object of which we can still take a trustworthy observation? Figure 5 gives an impression where we stand today. It contains a *selection* of groundbased and space-borne instruments, and a small *selection* of celestial objects.

Please do not get caught up in details but note and enjoy the enormous range. Each block is a factor thousand both ways. Horizontally we have 18 decades of the spectrum shown earlier. Vertically we have over 20 decades in intensity. One fact I like to remember is that from the Sun to a bright star like Vega is nearly the same intensity ratio as from Vega to the faintest stars within reach of the Hubble Space Telescope; both steps are roughly 27 magnitudes = 11 decades. Another still amazing fact is that in the meter (radio) waves there are three about equally bright sources in the sky: the Sun, Cas A and Cyg A. Yet the farthest and nearest of these three have distances in the ratio of more than 13 factors of 10. The square of this ratio tells us how much brighter in radio waves the galaxy Cyg A is than our Sun.

4. A Book of Records

Stars, galaxies and the Universe: there is no way in which all the discoveries of the last decades can be squeezed into one lecture. They were made by the combined effort of many people, many countries and many ingenious techniques. Space-borne instruments take a large share. Of course, among the thousands of study topics in astronomy, some havens of rest remain, where the space age has not yet entered. But more often than not, a thorough review of *any* astronomical question nowadays must *also* refer to space observations. And many important areas depend very largely on space data.

Instead of rushing along the complete gallery of new findings, I have chosen to summarize the advances under a few simple headings.

THE BEST MEASURING ROD

The last ground-based effort to measure the astronomical unit was made in 1930. It gave – when the observations of the asteroid Eros at many observatories had been analyzed in ten years time – the rather disappointing accuracy of one hundredth of a percent. In present days, by timing the signals to and from spacecraft, as well as radar reflections, we have routine confirmation of such distances in numbers of 9 significant digits.

The more severe problem was and is, to extend the measuring rod to the stars and from there to the galaxies and the Universe. This task is being completely overhauled by the European satellite Hipparcos. The principle is to measure large angles in the sky in many orientations; somewhat like the astronomers whose work Ptolemy gathered in the Almagest may have done. But note the difference: the present work covers 100 000 instead of one thousand stars, and does so almost a

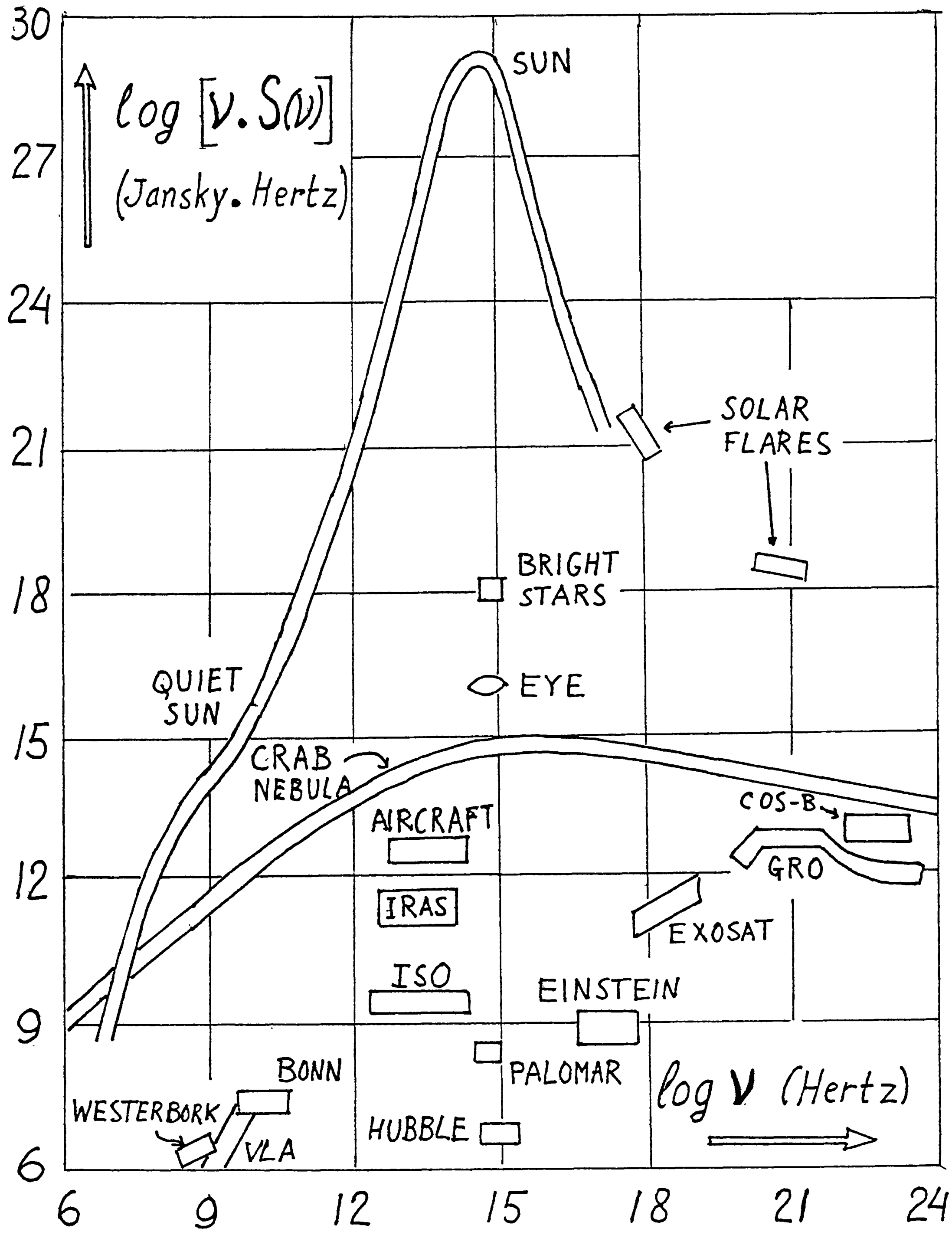

Fig. 5. Spectra of selected astronomical objects over the full range, together with the faintest intensities within reach of a sample of present instruments, both Earth-based and space-borne. One square is a factor 1000, vertically and horizontally.

million times more accurately. Launched early 1989, Hipparcos has already given a fantastic improvement. Stellar parallaxes are measured with an error level of 2 milli-arc sec, a factor 5 better than the average performance of ground-based observatories. This boosts by a factor 100 the volume of our galaxy that can be

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charted with precision and, therefore, the reservoir of objects from which secondary distance standards may be selected. Eventually, with research well into the next century, this will lead to far more reliable measuring rods to the distant reaches of the Universe than the still shaky measures which we have today.

THE BEST BEACON

How far can we look? And since distance is also time, how far back can we look? This question is too vague. Among the faint specks of light, which the most powerful telescopes can barely observe, many are ordinary nearby stars or galaxies. But among these specks are also extremely distant objects, suitable for studying the curvature of space and the earliest stages of evolution of our Universe. Which of these specks are the interesting ones? What we need is a beacon, a light that is not only of unusual power but that, by its characteristics, can be recognized as such.

In present-day astronomy these beacons are the quasars and the radio galaxies. Presumably the quasars are very massive black holes at the centers of certain galaxies. But saying so does not help much. Finding them and sorting out their properties is a long multi-spectral research program. We have progressed enormously in this program since the discovery of the quasars 30 years ago. But many further discoveries may be in store.

Initially the quasars were discovered as radio sources. Their small diameter, too small to be measured, gave them the name quasistellar and was prima-facie evidence that processes of very high energy went on in these objects. Two major surprises came soon after this discovery. First, their optical spectra showed a large redshift, usually interpreted as a Doppler effect due to the Hubble flow. Secondly, their short-time variability revealed an incredibly small linear size. Both facts corroborated the exceptionally high surface brightness of these objects. It became at once clear that the quasars would be very valuable beacons to measure the Universe. The hunt for more details and more quasars was open. It is still continuing in a friendly race between the ground-based and the space-based effort.

Quasars have now been observed to $Z = 4.9$. The most distant galaxy observed to date is at $Z = 3.8$. Figure 6 shows its contours observed with the Hubble Space Telescope, as presented at the HST symposium at Sardinia in spring 1992.

THE BEST CLOCK

Truly amazing progress again! For many centuries the fixed stars were fixed. No movement could be discovered that in any way could serve as the hands of a clock. When early this century attempts were made to measure the dispersion of light in space, the best available cosmic clocks were the eclipsing double stars: reading accuracy about 10 min. Now we have the millisecond pulsars, of which the pulses can be read with an accuracy of one hundred thousandth of a second. This gain in timing accuracy of over 6 orders of magnitude has opened amazing perspectives. For one thing, it has permitted many subtle checks on the general

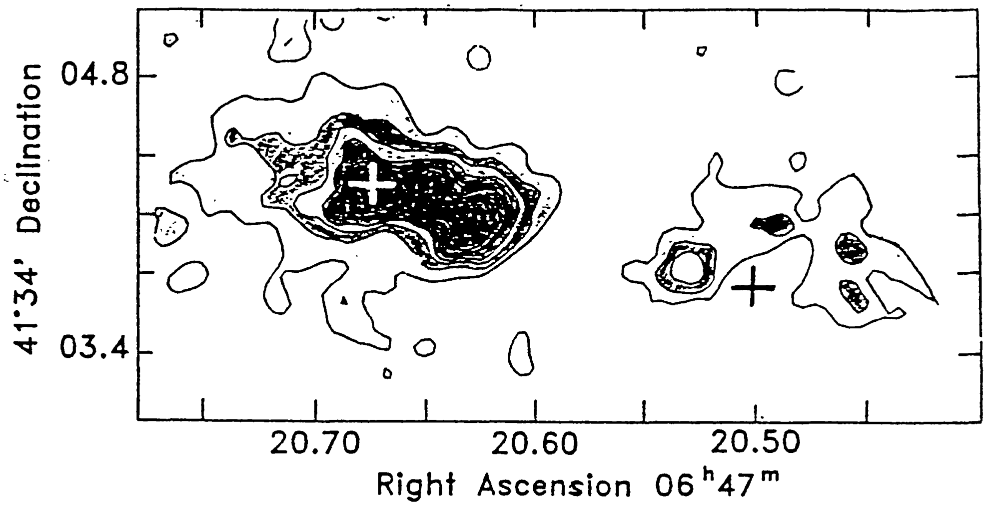

Fig. 6. The galaxy with the highest observed redshift ($Z = 3.8$). Contours: Hubble Space Telescope. Crosses: radio observations. From: G. K. Miley, K. C. Chambers, W. van Breugel, and F. Macchetto: 1992, *Astrophys. J.* **401**, L69.

theory of relativity, which have confirmed Einstein's bold guess. Some old pulsars are so regular that their reliability exceeds that of the best atomic clocks on Earth.

The pulsars are stars that have consumed most of their fuel. They were too heavy to become a white dwarf and too light to become a black hole, so they have collapsed into a neutron star. The existence of neutron stars is one of the few things in modern astrophysics that was inferred from theory *before* it was discovered from observation. The collapse to a small radius, of the order of 10 km, makes them spin incredibly fast: once around in the time of seconds or fractions of a second. Their remnant magnetic field causes an asymmetric emission of radiation which shows up as pulses quite like the swinging beam of a coastal light house. Curiously, the fast spin had been predicted but the pulsed nature of the emitted radiation had not. It was a very pleasant surprise.

The strongest sources in the gamma-ray sky are pulsars. Figure 7 shows one cycle of the Vela pulsar. Its pulses are synchronous over the entire spectrum, which is not so for other pulsars. Early 1992, after a search of many years, the enigmatic gamma-ray source Geminga was also found to be a pulsar; this one, however, with a puzzling lack of radio emission.

THE SHARPEST IMAGE

A sharp image requires a big telescope. Our eyesight is sharp because the pupil of the eye covers many thousands of wavelengths. Years ago, I used to explain in popular lectures that radio telescopes would be able to match this performance only if they were also made many thousands times larger than the wavelength, which meant covering a whole city. That much was correct. But I added: 'and that is impossible'; that addition turned out to be incorrect.

It proved possible to combine separate telescopes, even as remote as the different

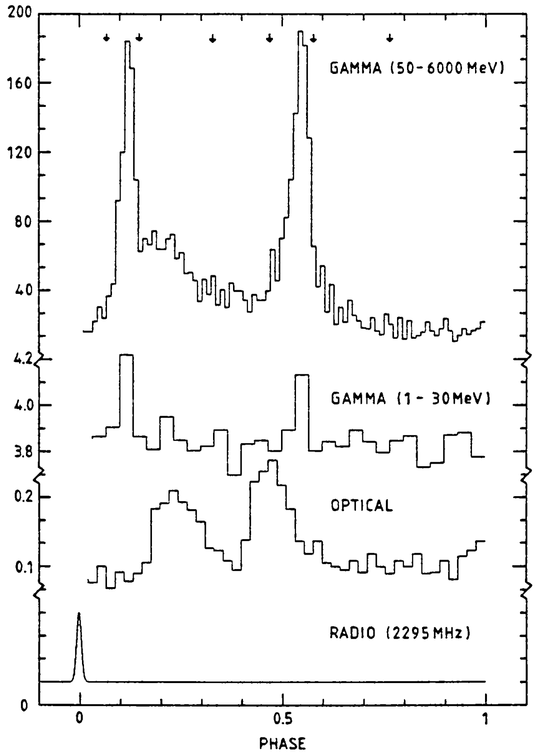

Fig. 7. Intensity versus time of the Vela pulsar during one pulse cycle (0.089 s), as observed in four domains of the spectrum. From: L. A. Grenier, W. Hermsen, and J. Clear: 1988, *Astron. Astrophys.* **204**, 117–132.

continents, into interferometers and synthesize the image of an object by computer. This so-called VLBI (very long baseline interferometry) has led to the remarkable situation that at present not the shortest (optical) waves but the much longer (radio) waves give the sharpest images. An example is shown in Figure 8(c), below. I am curious how long this situation will last, for the interferometry with optical and infrared wavelengths, which stagnated since the successes early this century, is also sharply on the rise with modern techniques.

Until now, VLBI is groundbased and hence limited by the size of the Earth. But space VLBI is just around the corner. The base lines will be both longer and more evenly spread with telescopes in orbit.

Unavoidable fluctuations in path length due to weather conditions limit the performance of present VLBI. Monitoring geodetic satellites helps to overcome this problem. On the 10 000 km baseline from Australia to California a precision under 1 cm has consistently been reached this way. At centimeter wavelengths, this results in a sharpness of one in a billion, a hundred thousand times sharper than the eyesight we are naturally happy with, and still a thousand times sharper than the best optical telescopes on Earth *and* in space.

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THE BIGGEST BANG

You will not be surprised if I tell you that the biggest bang is *the* big bang. This term was originally meant to ridicule a too bold speculation. It has become the standard expression for the current understanding of the origin of our Universe. Amazingly, this concept has so far been confirmed by many detailed discoveries. One of the conceptual obstacles has been removed by the COBE satellite, which measured the minute background fluctuations that may later grow into clusters of galaxies. When this picture appeared in the newspapers early 1992, it reminded me of those young couples proudly showing to friends an echograph of their yet unborn baby. You say politely: ‘how nice’, and you think: ‘wait and see’.

What is a ‘bang’? It is an explosive event in which accumulated energy is released when the retaining forces reach a critical point and suddenly give way. After that, one event triggers the next one, usually in a complicated sequence. I might demonstrate a small release of gravitational energy by gently pushing a glass of water off the table. It would include visible and audible effects and some hydrodynamics. But I won’t.

Explosive events occur in astronomy in all kinds and sizes. Consider for a moment a solar flare, which is a sudden release of magnetic energy. Such a flare is bigger than the Earth, yet on a cosmic scale ridiculously small. One reason for studying it is that we can see it in so much detail. We have ample statistics, we can study the magnetic field configuration before and after, and we can measure a multitude of after-effects on the Sun, in the solar wind, and even on Earth where a beautiful aurora may appear four days later. In spite of (or because of!) all this detail astronomers are still trying to figure out what exactly happens.

The most spectacular event on the scale of a full star is a supernova explosion. The opportunity to catch such an event sufficiently nearby for a detailed study is very rare. The supernova of 1987 in the Large Magellanic Cloud was such an opportunity and it was seized by hundreds of astronomers with all kinds of instruments.

Remnants of these supernova explosions remain visible for a long time. They all look different and are favorite study objects, both in optical and in radio astronomy. The young ones, like for instance CAS-A (about three centuries old) still are roughly circular; their forms immediately suggest where the explosion took place. The older remnants are getting entangled into the interstellar medium. Pretty soon they will become indistinguishable from the medium in which they move.

Supernova explosions drive the motions of interstellar clouds and of cosmic rays. My life-long fascination with this subject stems from its extreme remoteness from the classical ideals of cosmic order: not one shape, or one mathematical formula, but a lively interplay with the pre-existing interstellar medium. I have to confess, however, that since I first studied this subject, the data have proliferated and many distinctions have become necessary, which were previously ignored. But the picture of what drives what has not become proportionally clearer.

Next are the bangs showing up on the scale of a full galaxy. Here the big surprise took about a century coming, as I shall argue by one example. In 1918, many years after photographs of the most exciting nebulae taken by the Crossley reflector (which I mentioned in the history section) had been published, the files were cleaned and a descriptive list of some 800 duller objects observed over the past 20 years was published. One entry reads: '4486 ... Exceedingly bright; ... A curious straight ray lies in a gap in the nebulosity in position angle 20 degrees, apparently connected with the nucleus by a thin line of matter...'

When radio astronomy came, this 'dull' elliptical galaxy, now called Virgo A, turned out to be the fourth brightest object in the sky. Baade remembered the jet, photographed it in detail, and, inspired by speculations of others that it might emit synchrotron radiation, also measured its polarization. That was in 1956. The best pictures today are by the Hubble Space Telescope. Figure 8 shows three pictures of this jet. One made by Baade, one by the Faint Object Camera on HST, and one ground-based radio VLBI picture. The VLBI resolution is so enormous that this entire picture fits in the left-most white dot which in Figure 8(b) is the 'nucleus'.

Jets have been found in many galaxies. We now think of the 'machines' at the centers of galaxies as massive black holes. A tough question remained why these jets are so one-sided. The most likely answer seems that the 'machine' is symmetric with axes sticking out both ways, but that, since the velocities are close to that of light, only the axis pointing toward us shows up brightly. It is a relief therefore, that very recently a weak counter-jet in good old Virgo A has indeed been discovered. However, it is the details that count and, unfortunately, it is the details I have to skip in this talk.

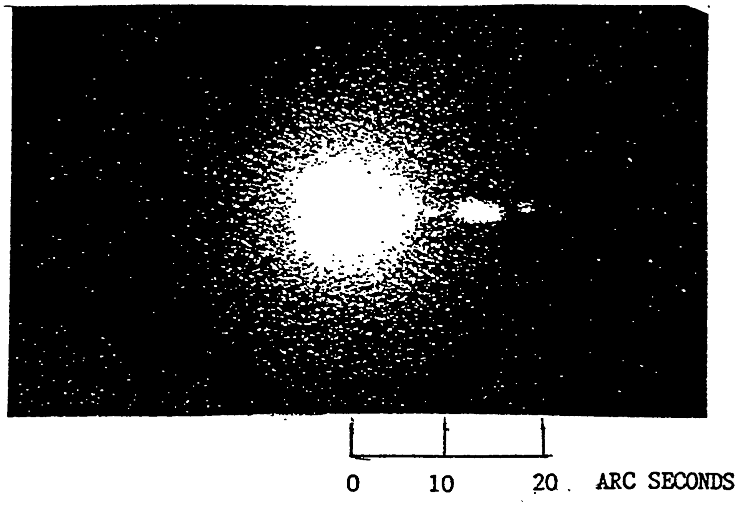
After this bang-bang-bang story, what more should I say about the *big bang*? Certainly this, that it deserves all the attention it gets from the professional astronomers and cosmologists, from the science writers, and from the large public. For me personally, my trail has led me elsewhere, partly because labour is needed in all parts of the field. Another excuse for shying away from these big questions is that, in somewhat smaller and nearer problems it is easier to notice the crucial moment when you start hitting your thumb instead of the nail.

5. Programmatic Issues

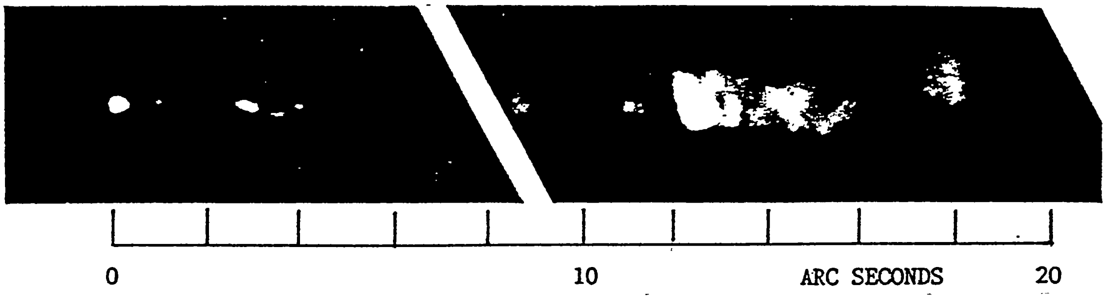
My last section contains a few comments on organizational and programmatic issues. As a retired professor I have the privilege to phrase these remarks in a detached manner. But many of you cannot afford to take this attitude. You are excited about your own specialty or reponsible for your own institute or your own instrument, or at least lobbying for it. You face the practical question what to do next: which mission to support, which paper to digest, in short, how to choose.

I love the discussions on these choices. But, now watching from the side line, I feel it would be both unfair and unrealistic to give this talk the appearance of an

(a)
Mount Palomar (1956)



(b)
Hubble Space Telescope Faint Object Camera (1992)



(c)
Radio VLBI (1989)

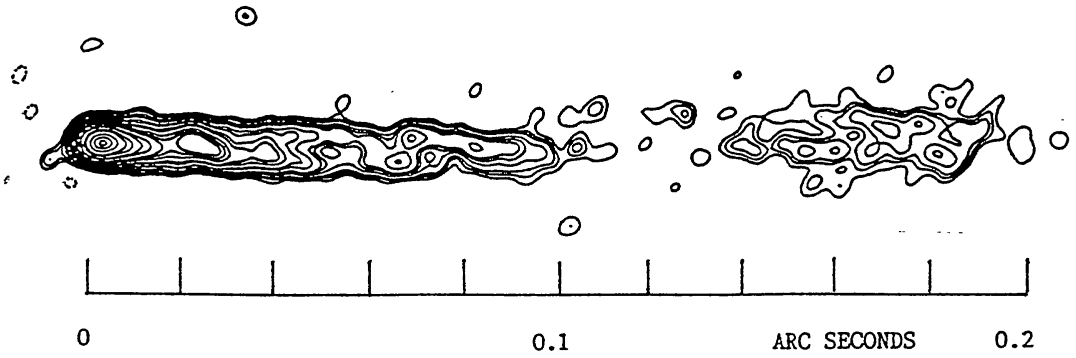


Fig. 8. Nucleus and jet observed in the elliptical galaxy Messier 87 = the Virgo A radio source. Note the very different scales. (a) Photographed by Baade in blue light (1956). (b) Obtained with Faint Object Camera of Hubble Space Telescope (1989). (c) At radio waves with the VLBI technique. From: M. J. Reid, J. A. Biretta, W. Junor, T. W. B. Muxlow, and R. E. Spencer: 1989, *Astrophys. J.* **336**, 112–120 (1989).

assessment report, which urges particular decisions about the next moves. So my remarks are confined to points of general strategy.

FRUITION RATIO

The choice nowadays is always between excellent plans. Blowing the chaff away until the one good grain is left, is the wrong metaphor, for it ignores the dedication and ingenuity that goes into *each* mission plan. I prefer the comparison with an apple tree, where (for no obvious reason) perhaps one out of ten beautiful blossoms becomes a ripe apple. Space policy makers do face the question how large this fruition ratio (some call it a frustration ratio) should be. Certainly, 10 is too large, but pretending it to be 1, while it is not really, is not a good idea either. Choosing a factor 3, like ESA does, may be about right. No matter how we arrange the process, some people will have to swallow their disappointment, switch field, or grow old before entering the promised land.

SCOPE

There is *no* absolute standard on how much money and manpower the world community should set apart for space science. The thesis (often implied but never stated) that everything that *can* be done *must* be done at short notice is untenable. It is good, however, to keep stressing the fact that there *is* plenty to be done. *If* plenty of money were available, a case could easily be made for having simultaneously 3 IUE's, 2 Hubbles and 3 X-ray observatories in orbit at all times, not even mentioning the major observatory on the Moon, about which our chairman already dreamed thirty years ago and that keeps coming up in a variety of contexts. Certainly, repetition or duplication of a successful mission should not be ruled out as long as viable observing programmes for it can be defined.

DEPTH OR OPPORTUNISM?

Arguments in reaching a decision are always mixed. The elements range all the way from deep philosophical importance to practical timeliness and outright opportunism. It is important that the persons involved in the advisory tasks, or in the decision making, should listen very carefully to these arguments and should probe how deeply they are rooted. The hope to find a clue to a deep question evidently is a much stronger argument than the desire to add another page to our stamp collection. However, nothing is wrong with opportunism. Since the early years of space science, when NASA generously showered the world with 'Announcements of Opportunity', opportunism has become a practical art.

COOPERATIVE VENTURES

Competition and cooperation figure prominently in many events during this Congress. Yet, I do not rank this as a separate issue. The choice to do something cooperatively or alone is just another example of practical opportunity. It is simpler to do things alone, *if* you can, rather than having to go through 20 versions of a memorandum of understanding, or having to learn the latest slang.

A good cooperation may result in a very positive cross-fertilization. I remember as a fine example the lively team of persons with 5 different native languages, which was building together the COS-B satellite. Evidently, in any cooperation, honesty in the negotiations and sticking to your promises is imperative. I cannot stress this enough!

BIG VERSUS SMALL

An often recurring dilemma is big versus small. Which is better, faster, and more cost-effective when it comes to designing space science missions, a small or a large one? The arguments sometimes became so heated that the words ‘large’, ‘small’, or ‘cheap’, were adopted as parts of the *names* of satellites; from which later they had to be dropped when it turned out that the satellites were not so large or so cheap after all. LST (L for large) became ST, later HST; ROBISAT (BI for billig = cheap) became the very successful ROSAT.

Those of you who would wish to study the large versus small case in a more classical context might enjoy reading a booklet which appeared 354 years ago in my home town. Here, in its ‘Dialogues and mathematical demonstrations concerning two new sciences’, Galileo starts out precisely with this big versus small question! One of the quotes (not the full dialogue) reads: ‘The larger the machine, the greater its weakness.’

REALISM NEEDED

I hope that this warning has become an unnecessary reminder, but unfortunately it was not always. Let me simply quote from Feynman’s (1987) report after the Challenger disaster: ‘Reality must take precedence over public relations, for nature cannot be fooled.’

WHAT ORGANIGRAM?

When the decision to do something has been taken and the money has been found, a division of labour is required. You need an organigram. I miss the endless meetings where these organigrams were discussed. My favourite one, however, is a cartoon by the Argentine artist Quino. It shows a boat with four men calling by megaphones the strokes and one pulling the oars. I love its subtle irony and I know that many of my hard-working colleagues easily identify with the one rower. So I was honestly surprised to see somewhere a headline which seriously read: ‘The first rule of project management: Don’t do it; get it done.’ The cartoon is also a personally precious memory to me, because it is from a booklet which the late Carlos Varsavsky gave me at the occasion of the Cospar meeting of 1963 in Mar del Plata.

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