is the editor of the recent IEEE Press volume of reprints on *Biological Effects of Electromagnetic Radiation*.

Dr. Osepchuk was National Lecturer (for 1977–1978) of the MTT Society (IEEE) on "Microwave Radiation Hazards in Perspective." In addition, he was the General Chairman of the *1978 Symposium on Electromagnetic Fields in Biological Systems* which was co-sponsored by IEEE-MTT-S and IMPI. He was on the Program Committee and a Session Chairman for a Symposium on "Health Aspects of Non-Ionizing Radiation" which was held on April 9–10, 1979, under the sponsorship of the New York Academy of Medicine.

He is a Fellow of the IEEE and the International Microwave Power Institute, and member of Phi Beta Kappa, Sigma XI, and the Bioelectromagnetics Society. He is a past chairman of the Boston Section of the IRE Professional Group on Electron Devices, a past member of the National Administrative Committee of the IEEE Group on Microwave Theory and Techniques and the Board of Governors of the International Microwave Power Institute. He is also a member of various committees of ANSI C95 (Chairman of Subcommittee 2 and Secretary of Subcommittee 4), the Association of Home Appliance Manufacturers (AHAM), and is presently a member of the IEEE Committee on Man and Radiation, and the National Administrative Committee of the IEEE Society on Social Implications of Technology.

In recent years, he has helped organize seminars for medical, legal, and executive personnel on effects and hazards of electromagnetic energy (the Homestead Seminars). He chaired an organizing committee in 1983 which led to the formation of the Electromagnetic Energy Policy Alliance (EEPA). This Alliance was founded by eight leading manufacturers and users of electromagnetic energy and is aimed at technical and public information activities which will enhance a rational perspective towards electromagnetic energy associated with modern electricity and electronics.

50 Years of Radio Astronomy

PETER G. MEZGER

I. Introduction

CONTRARY to most other branches of science, the birth of radio astronomy can be very accurately pinned down. In the early thirties Carl Guthe Jansky, an engineer at Bell Telephone Laboratories, was investigating atmospheric noise at 14.6-m wavelength with a highly directional antenna. He found that the antenna noise attained a maximum which shifted in time by 4 min per day, the difference between stellar time and solar time. He identified the direction of the maximum intensity with the position of the center of our Galaxy. He had discovered what we now know to be the diffuse galactic synchrotron emission, caused by relativistic electrons, which gyrate in the galactic magnetic field. Jansky published his discovery of the galactic origin of the observed antenna noise in the *Proceedings IRE* in 1933. Therefore, this year, we celebrate the 50th birthday of radioastronomy.

Jansky's discovery was first taken up by Grote Reber, an amateur astronomer, who built his own radiotelescope using a parabolic reflector. He made the first sky survey at a wavelength of 1.9 m and published his first map of the radio sky in 1944. Fig. 1 shows how the "radio"-Galaxy looks if seen with a modern, high-resolution telescope such as the 100-m telescope at Effelsberg (Fig. 2).

Contrary to the optical spectrum a very broad-band continuum emission is the dominant component of the cosmic radio radiation. It was therefore close to an astronomical sensation when in 1951 Ewen and Purcell discovered the 21-cm hyperfine structure line of atomic hydrogen, the most abundant element in interstellar space. The possibility of a detection of this line was predicted in 1944 by a Dutch graduate student, Hank van der Hulst.

Optical spectral lines need for their excitation temperatures of some thousand degrees Kelvin, while radio spectral lines can be collisionally excited already at temperatures of a few degrees Kelvin. Optical observations, therefore, relate predominantly to hot ionized gas such as stellar atmospheres or HII regions. Radiospectroscopy, on the other hand, with the detection of the Hλ 21-cm line and a series of detections of (today more than 200) molecular spectral lines, opened for astronomy a completely different window. It allows us for the first time to observe the very cold interstellar gas and especially the interior of giant molecular clouds out of which stars form.

Development of advanced microwave technology during World War II had a tremendous influence on the development of radio astronomy after 1945, providing both the equipment and the well-trained engineers and physicists, who became the first generation of radioastronomers. The half power beam width (HPBW) θ_A of the antenna characteristics of a radio telescope with aperture diameter D is given by

$$[\theta_A/\text{arc min}] \simeq 4.2\;10^3\;\lambda/D$$

with λ the wavelength. For the 100-m telescope (the largest fully steerable telescope) at a wavelength of $\lambda = 2$ cm, the HPBW (or angular resolution) is only ~ 1 arc min, comparable to the angular resolution of the naked human eye. This has to be compared with the angular resolution of

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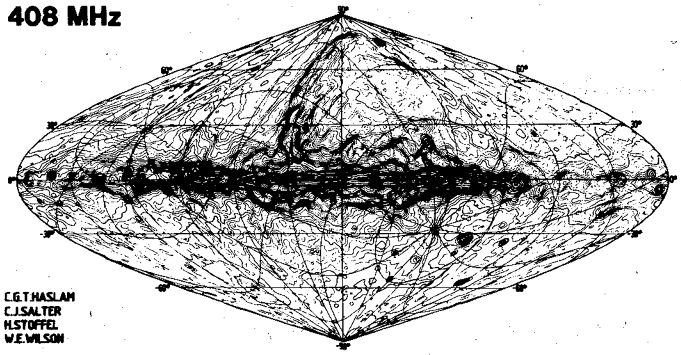

Fig. 1. Radio picture of the Galaxy at 430 MHz ($\lambda = 70$ cm), observed with the MPIfR 100-m telescope (northern sky) and the Parkes 60-m telescope (southern sky; observations by Haslam, Salter, Stoffel, and Wilson). The radiation is primarily synchrotron emission.

Fig. 2. The MPIfR 100-m telescope at Effelsberg, 40 km west of Bonn. The back-up structure of the telescope is designed as homologous structure, which deforms under gravity but maintains a paraboloidal shape. It is routinely used for wavelengths as short as 6 mm. (Built by MPIfR with Krupp and MAN.)

optical telescopes, ~1 arc s, which is not determined by the diffraction pattern of the reflector but by atmospheric turbulences (also referred to as "seeing").

The low angular resolution of the small single-dish radio telescopes available after the war was a major handicap during the early days of radio astronomy, because it made an identification of radio sources with optically visible objects very difficult. The quest for higher resolving power led to the introduction of radio interferometry, where two or more single-dish antennas, placed at a distance d, observe the same radio source with two independent radiometers. The IF signals from the individual telescopes are correlated after compensating for the time-delay in the signals. The effective resolving power of such an interferometer is that of a single-dish telescope of aperture d. But in terms of a Fourier analysis of the brightness distribution of the radio source, such an interferometer observation provides only one Fourier-component, viz., that corresponding to the baseline d. Further development of radio interferometry resulted in aperture synthesis, where an

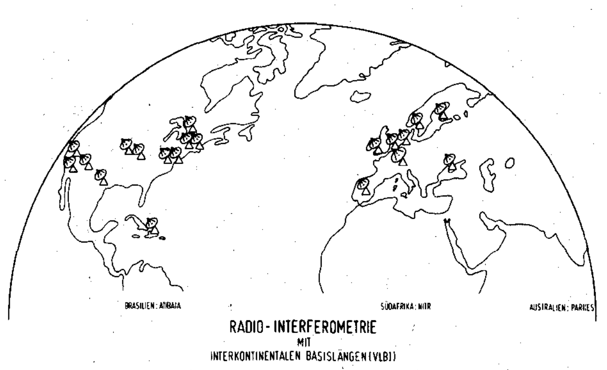

Fig. 3. Schematic representation of the U.S. and European VLBI networks. The 100-m telescope is a member of both networks and also operates the European processing center.

array of (typically 25-m) telescopes, together with the earth's rotation, provides a combination of different baselines and hence enough spatial Fourier components to reconstruct the brightness distribution of the radio source. The most advanced aperture synthesis telescope is the Very Large Array (VLA), built in New Mexico and taken into operation in 1976.

Contrary to optical astronomy the turbulence of the atmosphere does not impose a basic limitation to the angular resolution of radio telescopes. Hence it should be possible to build an array with spacings close to the diameter of the earth (the limit being set by the condition that all telescopes of the array must be able to observe the same source simultaneously). This led to the observing technique of Very Long Baseline Interferometry (VLBI), where existing radiotelescopes on the Eurasian and American continent are combined to form a gigantic array (Fig. 3). Signals are recorded on magnetic tapes and are subsequently correlated in special computers (VLBI processors). The European processing center is at the MPIfR at Bonn, West Germany. A high-resolution map of the nucleus of the (elliptical) radio galaxy NGC 315 is shown in Fig. 4.

Up to this point we were talking about observing techniques. Let me now return to astronomy. In recent decades, and to a large extent thanks to radio astronomy, we have learned a lot about the origin of the universe. It started to expand from a state of extreme density and temperature some ten billion years ago and stayed close to thermodynamical equilibrium during the first million years of its expansion. The physical model describing successfully these early stages of the universe is referred to as "standard big-bang model". It shows that about three minutes after the expansion has started, hydrogen, helium, and lithium (and their isotopes) but no heavier elements have formed. About 700000 years later the universe has cooled down to 3000 K, at which temperature free electrons and hydrogen and helium nuclei could combine and form atoms. Until this time radiation and matter were coupled through scattering of photons on free electrons. After most free electrons had disappeared (by becoming bound in atoms) the universe became transparent. Today the radiation field (or photon gas) has cooled down to 3 K

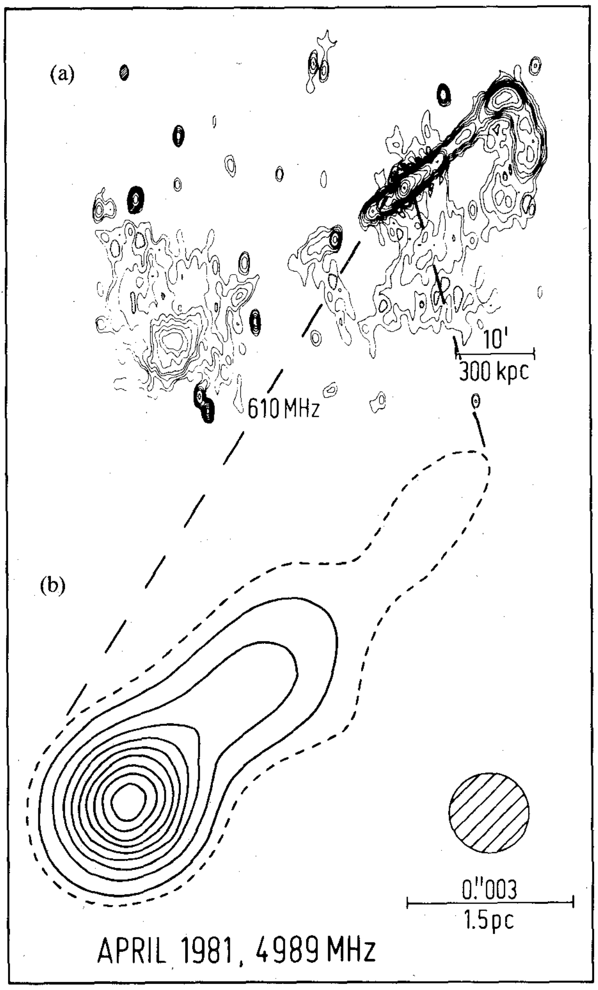

Fig. 4. A contour map of the (elliptical) radio galaxy NGC 315. The largescale map, made at 610 MHz by Bridle *et al.*, using the Westerbork synthesis radio telescope, has an angular resolution of 55 arc s. The lower map, made by Preuss, Pauliny-Toth, and Kellermann, using the 100-m telescope in conjunction with the U.S. VLBI network, has an angular resolution of 0.00075 arc s, which is a factor ~1000 better than the angular resolution of earthbound optical telescopes.

and its Planck spectrum is observed in the radio and submillimeter-range. The hydrogen and helium gas as a whole continued to expand but soon started to form huge clouds. These clouds (or protogalaxies) collapsed and formed the galaxies, which today are the building blocks of the universe. It appears that this process of galaxy formation was very efficient and that most of the matter in the present universe is contained in galaxies.

Galaxies are huge stellar systems similar to our own Galaxy, which contain typically some hundred billions of stars, which rotate about their center of gravity and in this way stabilize the system (i.e., at any point gravitational attraction is just compensated by centrifugal force). A similar type of equilibrium between pressure and gravity is found in stars like our sun. These stars have condensed out of the very diluted gas of a protogalaxy and have contracted as a consequence of their self-gravitation. The temperature rises in the center of the contracting protostar until temperatures of some ten million degrees Kelvin are reached. Then nuclear fusion of hydrogen into helium starts (this is, in principle, the same process that operates in a hydrogen bomb) and provides the energy (heat) which temporarily counterbalances gravity. In later stages of their evolution stars burn helium into heavier elements until, with iron, the nucleus with the highest binding energy per nucleon is reached. Then the central part of the star implodes and forms (depending on its mass) a white dwarf, a neutron star, or a black hole, while its outer shell is returned to interstellar space. This is the process through which the interstellar gas is enriched with elements heavier than helium and lithium. We owe the existence of our planet and its population to this so-called "chemical evolution" of the Galaxy. In the solar system and in the solar vicinity the heavier elements account for ~2 percent of the total mass.

Stars are the objects primarily observed by optical astronomers. Their surface temperatures range from 3000 to 50000 K and their emission (to a very crude approximation) follows Planck's radiation law. The emission of stars at radio wavelengths is negligible. Radio astronomy would never have become a viable branch of astronomy if matter existed only in the form of stars. That radio astronomy has, in fact, become the second most important branch of astronomy, is only due to the fact that the interstellar space (i.e., the space between stars) is filled with matter in various forms. In our Galaxy about 5 percent of the total mass exists still in the form of interstellar gas. Its existence was known already to optical astronomers, since part of the heavier elements condense out and form dust grains, which absorb and scatter star light very effectively. Also, in the vicinity of very hot and massive stars, the surrounding gas becomes completely ionized by the stellar ultraviolet (UV) radiation, and these so-called HII regions emit both a continuum and line spectrum which can be observed at optical wavelengths (see Fig. 6(a)). It was only radio astronomy, however, which could reveal the global distribution of neutral and ionized interstellar gas in the disk of our and other spiral galaxies. The whole concept of star formation and chemical evolution can be tackled only by radioastronomical (and, more recently, also by infrared (IR)) observations.

An example is shown in Fig. 5: a radio map of the Orion molecular cloud. The average density of the interstellar gas is 1 H-atom cm^{-3}. The first step in the formation of stars is the formation of huge clouds with relatively high densities, $\sim 10^3$ cm^{-3}, and very low temperatures (~ 10 K). Most of the hydrogen in these clouds is in the form of H_2 molecules which at these low temperatures have no observable spectral lines. But, besides H_2, there are molecules such as CO, H_2CO, and NH_3 (to name only a few of the more than 50 molecules, identified today in interstellar space) whose radio spectral lines can be observed and which tell us about the physical state of these precursors of star formation.

Another example is shown in Fig. 6: the radio and far infrared (FIR) spectrum together with an optical picture of the HII region NGC 6357. In the optical picture (Fig. 6(a)) one recognizes the dark ionized gas together with light

Fig. 5. The Orion molecular cloud as seen via the rotational lines of the CO molecule (observations by Kutner *et al.*). The contour lines (which are representative for the column densities of H_2) are superimposed on an optical picture of the Orion region. The molecular cloud appears as a black area in the optical picture due to its dust content. Deep inside the cloud, massive stars are forming whose radiation is completely absorbed by dust grains in the surrounding cloud and which is reemitted as IR radiation. At the upper and lower end of the cloud somewhat older stars have already ionized and dispersed the surrounding gas.

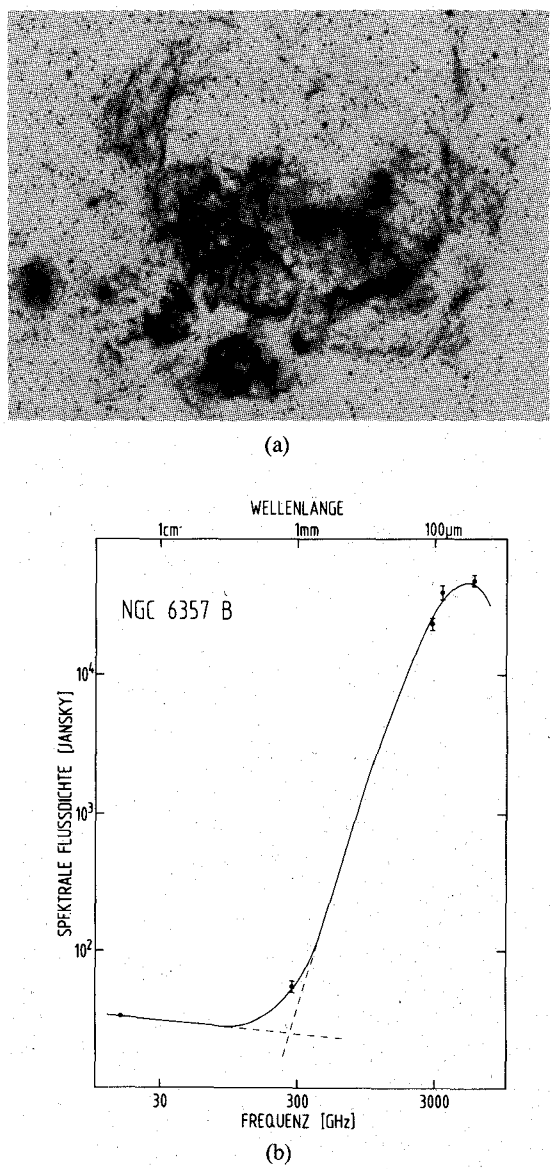

Fig. 6. (a) Photograph of the HII region NGC 6357. Dark regions indicate the radiation from ionized gas, light patches are regions where dust particles absorb the optical radiation. (b) Radio and IR spectrum of the HII region NGC 6357. The radio radiation is free-free emission, the IR emission is thermal emission from dust grains heated by stellar radiation (observations by Thum, Schmid-Burgk, Chini, Kreysa, Mezger, and Gemünd).

patches caused by absorption due to dust grains, which in part are located inside the ionized gas and in part are located in neutral gas surrounding the HII region. A large fraction of the stellar radiation eventually is absorbed by dust. This raises the temperature of the dust grains, which reradiate the absorbed energy, but at much longer wavelengths. The total radio and FIR emission (Fig. 6(b)) is the superposition of the free-free emission of the ionized gas (which is the same radiation mechanism that is also responsible for the microwave emission from gas discharge tubes used as noise tubes at centimeter- and millimeter-wavelengths) and the quasi-thermal emission from dust grains. Radio observations of HII regions in our Galaxy have revealed the existence of gradients in the distribution of the chemical elements and are the principal source of information about large-scale star formation.

Let me now turn to other galaxies. Our own Galaxy is a regular spiral galaxy whose spectrum from the short radio to the far UV wavelength range is shown in Fig. 7. The radio emission is a superposition of free-free and synchrotron radiation. The spectrum is dominated by the IR emission, which is reemission of absorbed stellar radiation by dust particles (1 mm $> \lambda >$ 1 μm) and direct stellar emission (10 μm $> \lambda >$ 0.09 μm). Beyond 0.09 μm, the Lyman continuum limit, photons can ionize hydrogen and thus are practically all absorbed in the vicinity of the stars which emit them. Only in the X-ray region does the interstellar matter become transparent again. If we want to compare energy per logarithmic frequency interval we have to multiply the flux density $S\nu$ by the frequency ν. In this case we would see that direct stellar radiation is still the dominant spectral feature and that only 20 percent of the stellar radiation of the Galaxy is converted into IR emission.

If all galaxies were like ours we could observe some nearby galaxies, but all information related to the large-scale structure of the universe would come through optical observations. However, systematic radio surveys of the sky revealed a new class of objects, termed radio galaxies and quasars (such as, for example, the elliptical galaxy NGC 315, whose radio picture is shown in Fig. 4), which are galaxies in some peculiar stage of their evolution, where enormous energies are liberated in their central regions. The nature of the "engines" providing these energies is not yet fully understood, but it is clear that it cannot be the fusion process that powers stars. More likely it is the

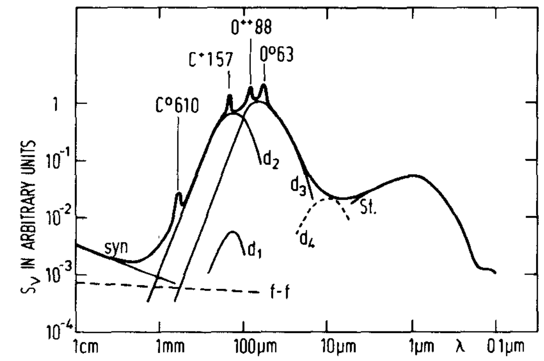

Fig. 7. The spectrum of our Galaxy, in arbitrary units. About 20 percent of the stellar emission (which dominates the spectrum at $\lambda \geqslant 10$ μm) is converted into infrared emission (1 mm–10 μm) through absorption and reemission by dust grains. The radio continuum emission has two components: Synchrotron emission caused by relativistic electrons gyrating in the magnetic field of the Galaxy; and free-free emission caused by electrons in a thermal plasma which collide with ions. Some of the strongest submillimeter and FIR lines emitted by the interstellar matter are indicated.

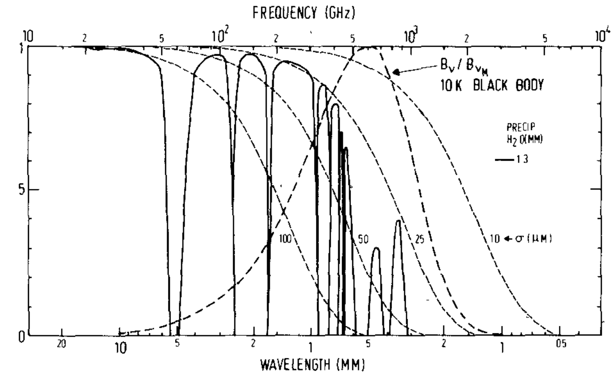

Fig. 8. Transparency of the atmosphere (full curves), computed for an atmospheric water vapor content of 1 mm, corresponding to an excellent observing day at altitudes between 3000 and 4000 m. Dashed curves show the decrease of antenna gain and aperture efficiency as a function of the rms deviation σ of the reflector from a best-fit paraboloid.

accretion of matter onto a very massive object, such as a black hole, a process which is by factors of ten more effective than hydrogen burning. Whatever this mechanism is, it succeeds to convert a large fraction of its total energy in the production of relativistic electrons with velocities close to the velocity of light. Gyrating in a magnetic field, these electrons emit synchrotron emission, which appears to be the dominant radiation mechanism in radio galaxies and quasars, which emit as much energy at radio wavelengths as in the optical region. As compared to the spectrum of our Galaxy shown in Fig. 7, the spectrum of a quasar would in essence be a straight line, $S_\nu \propto \nu^{-1}$, and hence the flux density at $\lambda = 1$ cm would be 10^5 times the flux density at $\lambda = 1$ μm. Thanks to an extremely fruitful cooperation between radio and optical astronomy such peculiar galaxies with highly active nuclei have been discovered, which are at a distance of about 90 percent of the radius of the universe or—stated differently—which we see in an evolutionary stage corresponding to an age which is about 10 percent of the present age of the universe.

In recent years the astrophysical importance of observations at millimeter-wavelengths and in the submillimeter and FIR regime has steadily increased. Most of the abundant interstellar molecules have their rotational lines in the millimeter and submillimeter range, and some of the major cooling lines (as shown in Fig. 7) lie in the submillimeter and FIR range. Thermal continuum emission from dust may eventually lead to the detection of protostars and protogalaxies. The spectra of some radiogalaxies and quasars appear to reach its maximum at submillimeter wavelengths. The extension of radio observations in the millimeter, submillimeter, and IR range meets, however, several problems. First, and beginning at 1.3 cm, several broad absorption lines of H_2O and O_2 make the atmosphere less and less transparent, until at 0.35 mm = 350 μm the atmosphere becomes completely opaque, to become transparent again only at windows around 20 and 10 μm, respectively (Fig. 8). It also becomes increasingly difficult to build large radio telescopes for observations at millimeter and submillimeter wavelengths. If G_0 and A_0 are gain and effective antenna area, respectively, of a perfect radio telescope, these quantities will deteriorate according to

$$G/G_0 = A/A_0 = \exp\left\{-16\pi^2(\sigma/\lambda)^2\right\}$$

with σ the rms deviation of the reflector surface from the best fit paraboloid. $\lambda \sim 10$ σ is usually considered as the lower wavelength limit of a radio telescope. Curves A/A_0 for various values of the rms deviation σ are shown in Fig. 8. The principal parameters that determine the accuracy of telescope reflectors for very short wavelengths are temperature gradients and the rms tolerances of the individual reflector panels.

Fig. 9 shows a 30-m telescope for millimeter observations, which the MPIfR, together with the companies Krupp and MAN, has just completed and will soon turn over for operation to the French–German radio observatory IRAM. It is located on the Pico Veleta in southern Spain at an altitude of about 3000 m. Such high altitudes are required for a low water vapor content of the atmosphere. The back-up structure of the telescope is thermally insulated to keep temperature gradients below 1°C. The reflector panels, made of aluminium honey comb, have rms tolerances between 20 and 40 μm. We are now in a design stage for a dedicated submillimeter telescope of 10 m diameter, which will be built and operated together with the University of Arizona. For the first time, the back-up structure and panels will be made of carbonfiber-reinforced epoxy, a material with a very low thermal expansion coefficient. With an experimental reflector panel, formed on a pyrex glass mould, the Dornier company was able to attain an rms accuracy of $\sigma \sim 4$ μm.

Radiometers used with these antennas are bolometers (for broad-band observations) and heterodyne receivers. With Schottky diodes used in open-structure mixers we have attained SSB noise temperatures of 20 000 K at 3 THz ($\lambda = 100$ μm) and there is no fundamental limitation to go to even shorter wavelengths. At wavelengths below

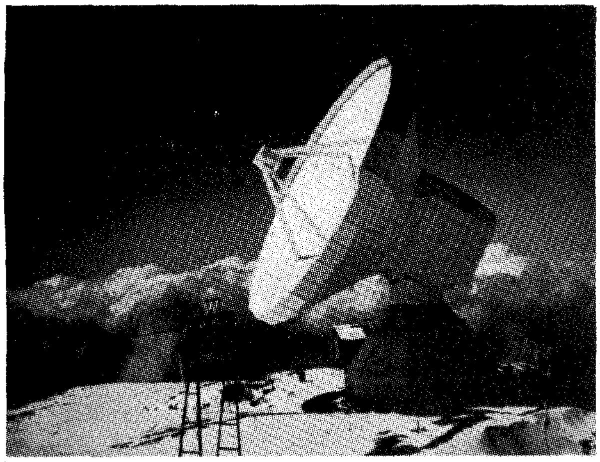

Fig. 9. A 30-m radio telescope for millimeter observations, built by the MPIfR on the Pico Veleta in southern Spain, in cooperation with the companies Krupp/MAN. This telescope will be used for observations at wavelengths as short as ~1 mm.

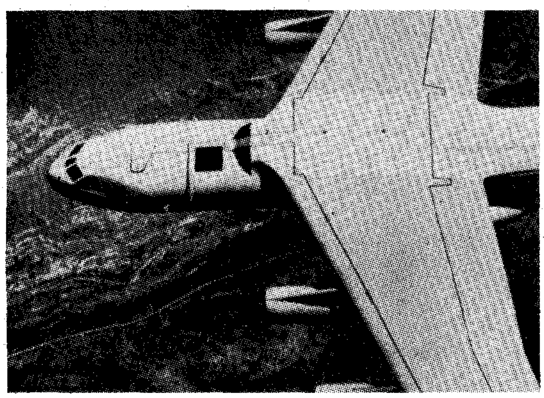

Fig. 10. NASA's Kuiper Airborne Observatory, one of the most successful IR observatories. It carries a 90-m telescope.

350 μm the atmosphere is opaque even at high altitude observatories, and space platforms must be used for observations. One of the most successful airborne observatories is the Kuiper Airborne Observatory shown in Fig. 10. It is a converted military transporter plane which carries a 90-cm telescope to altitudes between 11 and 14 km, well above the troposphere. This observatory is now operated by NASA for more than 10 years. Plans for a similar European Astroplane are being discussed under the sponsorship of the European Science Foundation.

Conclusion

Radio astronomy in the eighties is characterized by a quest for higher angular resolution and by a quest to extend radioastronomical observations in the millimeter, submillimeter, and FIR wavelength ranges. It is foreseeable that this quest will continue in the next decade and it necessarily leads to the use of space platforms both for advanced VLBI techniques and for submillimeter and FIR astronomy. The Infrared Satellite IRAS, which ended its observations last December, will give use new insight into the cold universe which is only accessible to mm/IR observations. A similar satellite, but devoted primarily to IR spectroscopy, has been chosen as the principal scientific project of the European Space Agency, ESA. Assessment studies are underway for free-flying space telescopes to be used for VLBI or submillimeter/FIR observations, respectively. Clearly, radioastronomy in the last decade of our century will go into space.

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After several years as an Assistant Professor at Bonn University he joined the Siemens Research Laboratories for three years. From 1963 to 1970, he was a Scientist at the National Radio Astronomy Observatory, Green Bank, West Virginia. He is currently Executive Director of the Max-Planck Institut für Radioastronomie and Professor at Bonn University. At the Institut he is, among others, responsible for the construction of both the 30-m telescope for millimeter astronomy and the 10-m telescope for submillimeter astronomy. He is also Chairman of the European Science Foundation's working group for the design of a European Astroplane. His main areas of research are: chemical evolution of galaxies, physics of the interstellar matter, and star formation.