50 Years of Continuous Revolution in Astrophysics and Cosmology

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1. Family and childhood

I was born in the middle of the Second World War in 1943 in Tashkent-a large multi-ethnic city on the former Silk Road, the capital of Uzbek Soviet Socialist Republic in the former Soviet Union. This was a very difficult time for the population of the Soviet Union. All resources were given to the people fighting on the fronts. The civil population was close to the edge of starvation. The Western part of the country, the most populated, was occupied, and a lot of people and industrial factories moved from Ukraine and Western Russia to the East of the country including Tashkent.

My mother and father married in October of 1941, several months after the war crossed the borders of the Soviet Union. Soon, my father was mobilized to the army. He was a civil engineer and an officer in the reserves—everybody with higher technical education was an officer in the army reserves in the Soviet Union at that time. He was drafted to build strategically important objects such as mines and factories in Central Asia, because this was what he was doing before joining the army. He only visited Tashkent several times for a day or two during 1942.

Much later, I was told by colleagues and friends of my mother, that she had no milk when I was born and she was spending most of her whole salary as the head of the pharmacy in the hospital for wounded soldiers to get two glasses of cow milk a day for me.

I hardly remember anything about the Second World War because I was only 2 years old when it finished. However, I remember difficulties of the post war years. The long lines for bread, sugar appearing for the first time in the shops after a long period of scarcity, and many beggars on the streets, often without legs or hands, but with a lot of medals and ribbons on their old military uniforms. Several of my close friends at school lost their fathers during the war.

From 1944 until 1954, my father, as an enlisted officer, was commissioned to build a dam for a strategic hydropower station in the semi-desert 130 kilometers from Tashkent. This power station was required to supply energy for uranium plant.

At the age of 5, when my sister was born, my mother sent me to her parents living in the exile in small Kazakh village in Southern Kazakhstan, not very far from Tashkent. When I returned to Tashkent at the age of 6, I did not remember a word of Russian and was fluent only in Kazakh and Tatar languages. Even now, when I hear Kazakh songs or see the semi-arid hilly grasslands I have some special feelings. This is the typical landscape of Southern Kazakhstan.

I remember warmly how, later, my grandfather would come on a horse to Tashkent, usually in the late morning and left well before the sunset. He died in 1951.

We were living in the central part of the "European" half of Tashkent, which at that time was still divided into 2 parts. The overcrowded old city, which was mainly occupied by the local Uzbek population, and the new city which was built by the Russian colonial administration after the city was conquered in 1865. The new Russian city was planned as a Roman military camp. It was of interest for me to see later, in the Ulugh Beg Astronomical Institute in Tashkent, the old military maps of the new part of the city and how it has expanded every 20 years.

In my class of 40 children, we had representatives of at least 12 different ethnicities from hundreds populating the huge territory of the Soviet Union. It was interesting to live in this multi-cultural environment together with Russian, Ukrainian, Ashkenazi and Bukhara Jews, Uzbek, Polish, Tatar, Lithuanian, Armenian, Azeri, German and Korean, speaking their mother tongues at home, but coming together at the big 4 story Russian school. Many of the Jewish, Ukrainian and Polish children moved to Tashkent during the war, after the Western parts of the country had been occupied.

Tashkent has changed enormously since that time. When I was finishing school, a lot of Uzbeki students were coming to study at the nearby Technical University, Medical University, and the University of Irrigation and Agricultural Machinery. In the 70s, the new city, the European part of the city, integrated with the local population even more, but I hardly know any Russians who moved to the old

Uzbek part of the city.

In 1990s, hundreds of thousands of people left Tashkent, mainly for Russia, Israel, USA, Germany and Canada.

That day in 1954 is still fresh in my mind, when a truck came close to our small house and two workers brought my father on a stretcher. They told me, as I was home alone with my sister, that father was unable to walk due to an acute episode of rheumatism and that he would now live at home and would not have to enter cold winter waters of the Syr-Darya River, one of the two largest rivers of Central Asia. My life changed completely on that day. That very evening before I went to sleep, my father told me several stories from the ancient history. For years, I was able to ask him any question and he always knew a simple and understandable answer or explanation. I was one of the best students at school and many of my teachers were unhappy when I asked questions because they were unable to answer them. I knew, however, that in the evening my father would answer these questions.

I enjoyed history, geography and literature much more than any other disciplines at school. I liked mathematics too but it was much more interesting for me to speak with my father and school friends about history. Also, I had no place to study mathematics more intensively than the school program provided. Only at the age of 15 I discovered the library with many math books and started to solve a lot of problems which were used in the entrance examinations to Moscow University. This was the advice of the math teacher at our school and I am still grateful to her. She separated our class into two groups: one of 3 or 4 boys and the other of 30+ children. To the small group she was giving very difficult problem sets and was grading our work much worse than to that of the rest of the class. However, at the end of the term, we all saw that our final grades were always excellent. This teacher told us where we could find books with hundreds of different problems, and repeated many times that we would be able to enter a good university only if we could easily solve any of the problems in these books. Finally, by the time I was finishing school at 17, I was solving the problems as easily as cracking nuts.

During the early spring of 1960, several months before graduating from high school, I won several mathematical Olympiads (competition among young people in mathematics) and got one of the two highest places in the mathematical Olympiad of whole Soviet Central Asia and Kazakhstan. Then I was sent for a week to Moscow to participate in the All Soviet Union Olympiad. I was not very successful at that Olympiad. In Moscow we stayed in the new (at that time) student dormitory in the main giant Moscow University building. I was very impressed by how good the life in that dormitory was and how good the student cafeteria was at Moscow University. My roommate was a student of mathematics in his 3rd year who told me that Moscow University is OK, but at the Institute of Physics and Technology near Moscow, the quality of scientific education is even higher.

When I returned home, my father told me that he was strongly against any attempt on my part to study history and become a professional historian. He told me that it is great to know history and its lessons well, but several of his close friends became scientists in the field of history and all of them were arrested and some of them lost their lives. He tried to explain to me that it would best to become a mathematician and at the same time get an education in some kind of engineering, such as electrical engineering.

As a winner of Central Asia mathematical Olympiad, I was invited to take the entrance exams to the local Tashkent university but decided to try to pass heavy entrance exams to Moscow Institute of Physics and Technology in the suburbs of Moscow. In the middle of June, I passed all school exams. My parents bought me a flight ticket to Moscow and I left home to conquer the world. These were the last days of June in 1960. I was 17.

2. Student in Moscow

The living conditions in the dormitories of the Moscow Institute of Physics and Technology in the city of Dolgoprudny were much worse than at Moscow University. The potential future students were living 5 in a room and I immediately realized that everyone was best in their class and they all wanted to enter the university. The number of applicants was 11.5 times higher than the number of places available. I still can not understand how it happened but I passed all exams and was invited to an interview, which was to decide who would be accepted among applicants who had passed all 6 exams, three (mathematics, physics and Russian) were written and the three oral were in mathematics, physics and Foreign language (German in my case).

I heard that at this stage there were still more than 2 applicants per place. I was very afraid that the KGB would have passed the information about the families of my grandfathers who in 1929 were both forced to leave the Tatar villages in Central Russia 400 km south-east of Moscow where they were living. Millions of educated or just doing well people were sent to exile during Stalin "collectivization" in 1929 and 1930. Many left their cities and villages understanding that in the opposite case their fate would be much worse. My paternal grandfather was arrested in 1929 and sent with his whole family (except my father who was a student at the high school in a nearby town) to a camp on Shilka River, one of the key tributaries of the great Amur River in eastern Siberia and the Russian Far East, to cut down trees. Two of my aunts 12 and 14 years old died in that compound which was part of the GULag system. Later the family escaped the compound and fled to Tashkent where people spoke similar language. Fortunately, information about my family from Tashkent authorities reached the Moscow Institute of Physics and Technology much later-after I was already one of the best students there. I was very lucky because the reference letter provided by my high school was excellent.

At the university I was good in mathematics. Although I was very proud when after two years of general education I was invited to become a student in chair of mathematics, I decided not to do this but to study physics. I am happy with that my decision.

3. Working with Yakov Zel'dovich

I met my future mentor academician Yakov Zel'dovich, in 1965, one year after he returned to Moscow from the classified city of Arzamas-16, where a lot of physicists and engineers were working on the Soviet atomic and hydrogen bombs. For this work he was decorated with three Golden Stars of Hero of Socialistic Labor. A person who had one star was considered enormously important in the Soviet Union. Zel'dovich had three, and this was the absolute maximum at that time.

My meeting with Zel'dovich completely changed my life. From the time I met him to the end of 1970, my life was full of festivity. Nearly every day he called me in the morning or I called him when I spent the night in Dolgoprudnyi, at my university dormitory, to discuss how the project was going or to fix a time for our meeting that day. He did this all 25 years we knew each other. I usually worked very late into the night, but he woke up very early and called me often around 8 in the morning.

I remember our first meeting, when he told me that he would like to solve astrophysical problems with me, and I told him that I would not like to work in astrophysics. The reason was that our department chair advised me: “You are a good student. Why do you wish to go to astrophysics? Astrophysics is a useless science.”

Zel’dovich was extremely clever. He said, “Please help me with two small problems and then we will return to the theory of fields.” When I solved these two problems, I never again wanted to return to the theory of fields because I recognized how interesting and how great astrophysics is, and then I spent whole my life in the field of astrophysics.

I became a student of Yakov Zel’dovich in March of 1965, at a time that was happy for him, and indeed for all astronomy. Many Russian astronomers remember the seminars at the Sternberg Astronomical Institute in Moscow in 1965-1968. The seminar series was led jointly by Zel’dovich, future nobelist Vitaly Ginzburg, and Joseph Shklovskii. Most well known astronomers of the Soviet Union were sitting in the hall and great physicists like Eugene Lifshitz or Andrei Sakharov occasionally appeared. And I remember the conference hall at the Sternberg Astronomical Institute, packed to the limit, with doors open on both sides, behind which clustered the latecomers, for whom there were no seats left. And I remember many young people, who later became the flower of Soviet astrophysics.

I remember the first seminars after the discovery of relict (cosmic microwave background, CMB) radiation, when Zel’dovich talked, as if it were something obvious, about the dipole component as means for measuring the velocity of the Earth, and about the presence of a reference system that could be defined by this radiation. I remember how I first heard from him at these seminars about the quadrupole component in the case of an anisotropic universe, and the unavoidable existence of angular fluctuations of the background. Only a year later, reading “fresh” issues of Nature, Physical Review Letters, and Astrophysical Journal Letters (when they were finally reaching us), did I understand that there existed a level at which these things become evident, and cosmologists of this level in Cambridge, Princeton, and Moscow were able to seize the same ideas simultaneously. And then I realized for the first time that to be alongside Zel’dovich meant, at a minimum, to be at the world-class level.

4. Revolution in astrophysics

The late 50s and early 60s were not greatest times for cosmology and high energy astrophysics. Those who know astronomy, young people especially, will be shocked to hear that there “was no” cosmic microwave background (CMB) at all; it was discovered only in the middle of 1965. There were no black holes, stellar mass black holes, or supermassive black holes, and no quasars. All this was discovered later. No gamma ray bursts. Even neutron stars, which we consider now as trivial dead stars with multiple classes that we can enumerate: radio pulsars, millisecond, accreting and anomalous pulsars, X-ray bursters, and magnetars—none existed yet; nobody was observing them. We did not know anything about exoplanets, which are being discovered now around nearby stars. We didn’t know anything about Lyman alpha clouds. So much came to us during last 50 years, and I really think that this was a great revolution in astronomy. Maybe, astronomy never had such a great time as these 50 years, which started at about the time when I joined the group of Zel’dovich.

In many research groups across the globe the start of this revolution occurred in the late 50s when very strong and experienced scientists working on the atomic bomb program, radar physics, and many other military applications of physics returned to fundamental science and some of them got the possibility to work in astrophysics, radioastronomy, and cosmology. This was exactly the case at least for the Zel’dovich group in Moscow, Martin Ryle group in Cambridge, Robert Dicke group in Princeton and many others in USA. Another reason for the experimental jump was connected partially with the development of ballistic missiles and the launch of Sputnik and next spacecraft with first simple scientific instruments aboard and continuing competition in space between the superpowers. These satellites opened an opportunity for astronomers to begin observations beyond the Earth’s atmosphere, which in turn, opened for them additional spectral bands of electromagnetic spectrum and celestial objects completely impossible to observe from the Earth’s surface.

It is necessary to be honest and admit that astronomers already knew a lot at that time. They knew well about the redshift of the spectral lines in the spectra of distant galaxies, about expansion of the Universe and the Hubble law. Scientists were spending their lives measuring with high precision the distances to variable stars, to galaxies of different types, trying to build the scale of cosmological distances.

Astrophysicists knew at that time that nuclear energy is powering our Sun and other stars. The rapid development of nuclear physics enabled them to understand and explain the origin of practically all chemical elements produced during the evolution of stars and released to interstellar matter during giant explosions accompanying their death and collapse. Astronomers were working actively on the theories of the formation of stars, planets and galaxies from diffuse interstellar matter. But this was a much slower process.

5. X-Ray astronomy and the theory of accretion onto black holes

By the end of the 60s and beginning of the 70s the first flights of rockets and high altitude balloons with X-ray detectors aboard led to the discovery of the brightest X-ray sources on the sky and the existence of isotropic X-ray background radiation. However modern X-ray astronomy began with the launch of the UHURU spacecraft in the end of 1970 by the team lead by Riccardo Giacconi. These first experiments with X-ray detectors above the atmosphere attracted the attention of theorists to compact dead stars, like white dwarfs, neutron stars and black holes, and to the process of accretion. Accretion is the gravitational capture and infall of matter onto the surface of, for example, a neutron star having huge gravitational potential. A neutron star has a radius of the order of 10 km when its mass should be close to the solar mass, M_{sun}. In the simplest approximation, the radial fall of a body onto the surface of a neutron star will accelerate this body up to a velocity exceeding half of the speed of light. The energy release near the neutron star surface should reach the value of the order of 0.15 mc^2, where m is the mass of the body. Due to the very small surface area of the neutron star, the energy released during strong accretion can be radiated only in X-rays, so high is its surface temperature.

Even more exotic objects at that time were black holes, one of the most interesting predictions of the general theory of relativity, and the theory of stellar evolution. In 1970 my younger colleague, Nikolai Shakura, of Moscow University, and I became very interested in the problem of accretion onto black holes and ways to make these mysterious objects visible.

After more than two years of hard work, we submitted a paper in which we introduced the theory of disk accretion onto black holes. The main idea of this theory was very simple. Astronomers knew that the majority of nearby stars in the solar vicinity are binaries: two stars rotating around the center of their mass. When one of these stars dies and transforms into a neutron star or a black hole, the possibility of the gas flow from a normal star to a dead star arises.

Gas flowing toward a black hole from another star can not fall radially onto a black hole because it has significant angular momentum. This situation is very similar to the case of our Earth, which rotates around our Sun with an angular velocity close to 30 km/sec and does not fall onto the Sun because the gravity attraction toward the Sun is exactly compensated by the centrifugal force. It was well known from the theories of the formation of the Solar System that at the initial stage of formation there was a protoplanetary disk rotating around the protoSun and supplying additional mass to our star. The instabilities in this disk lead to the formation of planets, which we are observing even now when the disk has completely disappeared. The giants in the 18th, 19th and first half of the 20th centuries created the theories of formation of protosolar cloud and proposed that viscosity in the protoplanetary disk might lead to the formation of the mechanisms making it possible to transfer the angular momentum toward the outer boundaries of the disk and permitting the slow spiraling of the matter in the disk toward the gravity center. In the paper with Nick Shakura we were able, using the nondimensional parameter *alpha* describing the efficiency of turbulent and magnetic viscosity, to find the key properties of the accretion disk including its thickness, radial velocity of matter, internal and surface temperatures. The simple formulas describing the dependence of the energy release and the surface brightness of the accretion disk on the distance from a black hole were found. It is important to mention that the energy release in every point of the disk was connected with the viscous heating or dissipation of turbulent motions and magnetic fields created by the large scale instabilities. The source of the energy for the turbulence and finally for the luminosity of the accretion disks was the gravitational energy of accreting matter. There is a marginally stable orbit at a distance equal to 3 gravitational radii for a nonrotating black hole having Schwarzschild metrics. It is important that the stress between different layers in the differentially rotating disk diminishes to zero near this marginally stable orbit. As a result, in the simplest cases we could observe only energy released in the disk beyond the marginally stable orbit. A body with mass *m* moving in the disk from infinity to this marginally stable orbit should release and radiate $0.058mc^2$, where mc^2 is the rest mass energy of a body. For the flow at the rate M_{dot} the luminosity of the disk should be equal to $0.058\ M_{dot}\ c^2$.

The surface brightness of the disk rapidly increases toward the black hole and more than half of the total luminosity is released at distances smaller than 20 gravitational radii but exceeding the radius of the marginally stable orbit.

We normalized the luminosity of the disk to the Eddington critical luminosity. The origin of this limiting luminosity is very simple. In the spherical problem the light pressure force onto an electron at any distance R from the source of radiation is exactly equal to the gravity force of attraction of a proton to the black hole only for one value of the luminosity, which is the Eddington luminosity. At lower luminosities gravity force exceeds the light pressure force. At higher luminosities the light pressure force dominates. The numerical value of the Eddington luminosity Ledd=10^{38}(M/M_{sun})erg/s is huge. For example for an object with a mass equal to the mass of the Sun, it exceeds the solar luminosity 30,000 times.

In the following paper with Nikolai Shakura published in 1976 we demonstrated that the theory of disk accretion is applicable also in the case of accretion onto supermassive black holes in active galactic nuclei and even in the case of the brightest objects in the Universe, quasars. Masses of accreting black holes in quasars often exceed a billion solar masses, i.e. their Eddington luminosities exceed by many thousand times the luminosity of our whole Galaxy. And now astronomers are able to detect hundreds of thousands of such extremely luminous objects on the whole sky. To maintain such high luminosity they should accrete, every few seconds, a mass equal to the mass of our Earth.

When the mass of a black hole and its accretion rate are so high, the radiation pressure within the disks exceeds, by many times, the pressure of normal plasma. These disks are radiation dominated. The analysis of the stability of disk flow showed that under these circumstances different instabilities arise, leading to a time variability of the disk radiation.

We were very brave and were even considering the case when the mass inflow through the outer boundary of an accretion disk exceeds the Eddington value necessary to produce the Eddington luminosity. It was already obvious at that time-in 1972-that huge radiation pressure would lead to a strong outflow of matter from the inner regions of the disk and even to the formation of relativistic jets.

Later I was strongly interested in the problem of accretion onto neutron stars in low mass binary systems. These are very old stellar systems, billions of years old, in which one star is a tiny white dwarf or low mass normal star and the other is a more massive neutron star with a radius of only 10 km. And the dwarf star supplies matter for accretion onto the neutron star. This gas forms an accretion disk which comes very close to the surface of the neutron star. Our Sun is bigger than the whole dimension of such a binary system. X-ray astronomers have detected several hundreds of such systems in our Galaxy.

Old neutron stars often have low magnetic fields ($< 10^8$ Gauss). Such magnetic field can not prevent the accretion disk from reaching the surface of the neutron star. Let us consider a neutron star to be like an extremely carefully polished billiard ball, with a radius on the order of 10 kilometers. In this case matter infalling from the accretion disk rotates around a neutron star with a Keplerian velocity close to half of the speed of light. And these are not particles—this is the flow of collisional gas. It’s extremely interesting how this gas loses its kinetic energy in the narrow boundary layer in the vicinity of the neutron star’s surface. The energy release in this boundary layer is so strong, that the radiation pressure within the boundary layer is hundreds and thousands of times higher than the thermal pressure of the accreting gas.

The community of X-ray astronomers and high energy astrophysicists in the world consists of several thousand scientists. More than 20 X-ray spacecraft were launched into the orbit to help discover thousands of X-ray sources and to understand their nature. I should especially note the contribution of the Japanese series of X-ray spacecraft, starting with HAKUCHO. Prof. Minoru Oda told me several times that “small is beautiful” because Americans and Russians were trying to launch huge spacecraft, while Japan was launching small spacecraft, but they functioned very well and provided extremely interesting science. And there were also GINGA, TENMA, ASCA, SUZAKU. There is the Japanese all-sky monitor MAXI on the International Space Station. We all dream about the time when the Japanese NEXT spacecraft will be in the sky with sophisticated X-ray calorimeters.

I was very happy to meet and have good relations with the leaders of the Japanese high energy astrophysics program. I remember warmly my meetings with Satio Hayakawa and Minoru Oda; unfortunately, they are no longer with us. But I am happy to speak rather often with Yasuo Tanaka, a great scientist. I remember well my frequent visits to ISAS (Institute of Space and Astronautical Science) when Hajime Inoue was the director there. I must add that here in Kyoto you have a successful X-ray experimental group which was led for many years by Prof. Katsuji Koyama, and you have an excellent group of theorists who are working in high energy astrophysics under the leadership of Professors Shin Mineshige and Shoji Kato. There is also a world recognized group of cosmologists in the Yukawa Institute for Theoretical Physics at Kyoto University.

6. Cosmic Microwave Background Radiation (CMB)

In 1965 Arno Penzias and Robert Wilson discovered Cosmic Microwave Background Radiation, which fills our Universe and has a temperature close to 2.7 degrees on the Kelvin scale. This great discovery has completely changed cosmology and provided unique information about the history of our Universe.

I remember well the shock reaction in Moscow connected with this discovery. My mentor, Zel'dovich, had been developing for more than 5 years the "cold model of the Universe" as an alternative to the "hot model of the Universe" proposed by George Gamow, a Russian scientist working in the United States, at the end of the 1940s. Hot model was predicting the existence of the black body radiation filling whole our Universe.

Zel'dovich told me several times that any theory should be proven by experiment. This was the reason why he immediately changed his mind after the discovery of CMB, never again mentioned the cold model and started to work on various aspects of CMB cosmology. I was very lucky because I joined Zel'dovich a little before the discovery of CMB and he already knew that I was interested in the work on interaction of matter with radiation under extreme astrophysical conditions.

Cosmic Microwave Background Radiation, as we know now, is practically isotropic. It fills our Universe, and in every cubic centimeter of the space between galaxies we will find 400 CMB photons. The average density of atoms or baryons and electrons is much lower: the density of photons in the Universe exceeds it by more than a billion times. Our Universe is radiation dominated. It is impossible to create so huge amount of photons in stars or other known sources of radiation. CMB radiation is an intrinsic property of our Universe. Its brightness does not depend on the direction of observation—it is practically isotropic. Today we know that CMB has the best black body spectrum among all celestial objects. No deviations from the Planck formula for the black body spectrum have been detected yet.

Our universe is expanding, and the current temperature of radiation is as low as 2.725K. Expansion should lead to the adiabatic decrease of the temperature. This means that the radiation temperature was higher in the past, i.e. it increases with redshift. Thus, at sufficiently high redshift the density and temperature will be high enough to permit nuclear fusion reactions of helium from the primordial mixture of protons and neutrons.

I remember well that when I'd just become a student of Yakov Zel'dovich in the spring of 1965, I was reading a paper by Prof. Chushiro Hayashi, future Kyoto Prize winner. This paper was about neutrinos and positron-electron pairs in thermodynamical equilibrium with the radiation field and nucleosynthesis in the hot Universe when the Universe was only a few minutes old. It is important to mention that Gamow and his younger colleagues, Ralph Alpher and Robert Herman, thought initially that it would be possible to create, during the first minutes of the Universe expansion, all observable chemical elements. They didn't know cross sections for all nuclear reactions, which were classified at that time, and they did not know that it's extremely difficult to combine three helium nuclei into carbon. Today we know that the bulk of the helium in our Universe and practically all deuterium, helium-3 and even the lithium in our batteries, laptops and telephones were produced during the first three minutes of the expansion of the Universe. All elements heavier than carbon were created in massive stars, where densities and temperatures permitted the crossing of the threshold of carbon formation from three helium nuclei.

6a. CMB spectral distortions due to energy release in the early Universe.
The black body photosphere of our Universe.

In 1965 just playing with different cross sections I recognized that Thomson scattering of CMB photons on electrons is the most important mechanism of opacity in the early Universe. I was very surprised, when making the simplest estimates, how incredibly small the Rosseland optical depth of the Universe was due to bremsstrahlung. It was clear that it was necessary to study in detail the physical processes that could affect the CMBR spectrum: is it at all possible to create the blackbody radiation during the evolution of the universe?

A lot of different mechanisms of the energy injection in the early Universe were proposed later by theoretical physicists and cosmologists. Today we all are interested for example in a possibility to detect the energy release due to annihilation of the dark matter or decay of the particles not detected yet in physical labs. Obvious questions arise: what type of spectral distortions will these processes leave on the CMB spectrum. Astrophysicists usually assume that the Thomson scattering does not change the frequency of photons and therefore does not influence the spectrum of CMB radiation. But after listening to lectures at the University I remembered that Compton scattering by near-relativistic electrons changes the photon frequency and creates photons (double Compton). I had already in my hands an article on the subject by Aleksandr Kompaneets (1956), and a book, Quantum Electrodynamics by Akhiezer and Berestetsky, still one of my favorites, on the bookshelf in my dormitory room. I learned a lot from Kompaneets' article. Photons, scattered on the thermal (moving) electrons are on average increasing their energy. When photon energy exceeds four times the temperature, recoil effect starts to dominate. As a result photons are redistributed by this process, named Comptonisation, over the frequencies. Finally Zel'dovich and I were able to find two key types of the CMB spectral distortions resulting from the energy release of any nature in the early Universe. These distortions are named now as y-type and Bose-Einstein distortion or μ-distortion of the CMB spectrum. In scattering by free electrons that preserves the number of photons the radiation spectrum relaxes to the form characteristic of a boson gas with nonzero chemical potential μ. Both types of distortions are shown in Figure 8.

However bremsstrahlung (and double-Compton emission) can create photons at low frequencies, which Comptonization can raise to higher energies, lowering ƒÊ, and even relaxing back to a true blackbody spectrum. *Full solution of the problem demonstrated that any energy deposited at redshift $z > 2x10^6$ would leave no trace in the observed relict radiation spectrum*. Later ($10^5 < z < 2x10^6$) energy release would lead to a Bose-Einstein spectrum distortion. For $z < 10^4$ any energy release will lead to the y-type spectral distortions (see Fig. 9).

Let us repeat that slow production of photons due to double Compton process and bremsstrahlung and their rapid redistribution along frequency axis permits to create practically ideal black body spectrum if energy release occurred earlier than redshift $2x10^6$. This epoch we can define as *the black body surface* of our Universe.

The precision of the present day space experiments is enormous.

Cobe-Firas experiment led by John Mather demonstrated that both y and μ -distortions of the CMB spectrum are very low (see experimental upper limits presented on the Fig. 10). Authors of PIXIE proposal submitted to NASA are planning to find these distortions even on the level of y and μ of the order of 10^{-8}. This corresponds to the energy releases on the level of 10^{-8} of the energy density of the CMB! One of the most important goals of future experiments is the detection of the energy release connected with the energy dissipation of the primordial sound waves in small scales unobservable by other methods.

6b. The recombination of hydrogen in the Universe

One of the most important moments in the life of our Universe is the time of hydrogen recombination. The expansion of the Universe leads to the decrease of the temperature. When its age is close to 400,000 years, the radiation temperature drops to the level of 4,000 degrees. At such a temperature, according to the textbooks of statistical physics, primordial fully ionized plasma should recombine and form hydrogen atoms.

In September 1966, I gave a talk at the All Moscow Astrophysics Seminar in the Sternberg Institute where I mentioned hydrogen recombination in the universe, and noted that, according to the Saha equation, it occured at redshift $z \sim 1300$. Dima Kurt, one of my closest friends at that time, came up to me after the seminar and asked: "And where are the Lyman-alpha line photons emitted by the recombining atom and displaced by the redshift?" I immediately explained that due to huge ratio of CMB photon density to the density of recombining atoms there would be a relatively small amount of the Lyman-alpha photons, and that they come to us in a range of wavelengths that was observationally inaccessible at that time.

But Dima's question sunk into my mind. The optical depth in the Lyman-alpha line is huge. The cosmological redshift caused these photons to very slowly escape through the long wavelength wing of the line. To our surprise, the extremely slow two-photon decay rate (8.1/sec) was more likely to happen than escape of Lyman-alpha photons through the wing of the Lyman-alpha line. Knowing the lifetime of the 2s level and the rate of Lyman-alpha photons escape through the wing of the line, it was not hard to calculate the hydrogen recombination process. In the paper published by Zel'dovich, Kurt and me in 1968 we demonstrated that cosmological recombination of hydrogen was delayed strongly relative to the simple Saha formula (see Fig. 11).

The Universe was optically thick before recombination, i.e. the mean free path of CMB photons was much smaller than the horizon. After recombination there were practically no free electrons left and the Universe became transparent; since then photons could propagate directly to us. Thus hydrogen recombination defines the last scattering surface. The importance of the Thomson scattering visibility function $V = \exp(-\tau)$□~$d-\tau/dz$ was recognized already in the paper with Zel'dovich published in 1970, when an approximate analytical solution for recombination was found. This function defines the properties of the last scattering surface. These beautiful terms were introduced much later. The shape of the visibility function is presented in Fig. 12.

In 1975, Victor Dubrovich pointed out that the transitions among highly excited levels in hydrogen are producing additional photons, which after redshifting are reaching us in the cm-and dm-spectral band. This band is actually accessible from the ground.

6c. Growth of adiabatic density perturbations in the Universe, CMB acoustic peaks and baryonic acoustic oscillations

It is well known since the classical paper of Eugene Lifshitz in 1946 how adiabatic perturbations grow in the Universe according to Einstein's theory of general relativity (GR). Nevertheless, it is possible to explain this process using a simple Newtonian approach and remembering the properties of Jeans gravitational instability.

Our universe was a unique object at the early stages of its expansion. The velocity of sound was close to the velocity of light, and therefore a Jeans wavelength was just a bit smaller than the horizon scale.

In the expanding universe (as in any object affected by Jeans' instability) density perturbations on scales smaller than a Jeans wavelength had to behave like acoustic waves.

In the very early universe only the growing mode of density perturbations survived, meaning all acoustic waves were launched with the same phase.

The sharp decoupling cut off fluctuations of different wavelengths at different phases. This led to a wonderful prediction of the quasiperiodic dependence of the perturbation amplitude after recombination on the length scale. This effect now is called the baryonic acoustic oscillations. (The presence of dark matter complicates this picture, but not the physical essence.) This quasiperiodic behavior in the distribution of baryons and electrons and their velocities, naturally, had to be reflected in the quasiperiodic behavior of the angular distribution of CMBR temperature. These acoustic peaks were discovered by the Boomerang, Maxima-2 and WMAP experiments.

7. Hot gas in clusters of galaxies and CMB

Clusters of galaxies are the biggest gravitationally bound objects in our Universe. Their masses are huge: they contain thousands of galaxies moving in the gravitational well of the cluster with velocities close to 1,000 km/sec. They are filled with hot intergalactic gas having temperatures of 10-100 million degrees and radiating in X-rays, which we detect now using X-ray satellites. In 1967, when I first time heard about the “missing mass” detected by Fritz Zwicky in the nearby clusters of galaxies, there were no X-ray satellites yet. The problem arose: *are there ways to detect hot gas in the clusters of galaxies using interaction of the hot gas with CMB photons?*

A beautiful and unexpected result came when the change of the photon frequency due to comptonization on the hot electrons was taken into account. Gas in clusters has a small Thomson optical depth. The rare single scatterings of a small fraction of the photons crossing the cluster defined the change of the CMBR brightness.

The CMBR brightness in the directions toward clusters had to decrease at centimeter and millimeter wavelengths. This was absolutely unexpected. The corresponding increase of the brightness in the sub-millimeter band did not excite anybody at the time.

When I was presenting my first talks about the effect, some physicists were skeptical because they thought that the diminution of the sky radio brightness in the direction of a cloud of very hot gas contradicts the laws of thermodynamics. Astronomers were very skeptical when I told them that the strength of the effect and its spectrum don't depend on the redshift, a measure of the distance to an object. This contradicted all the experience of extragalactic astronomy. It was very important to have so strong scientist as my mentor Yakov Zel'dovich behind me during these seminars.

A great moment for me was when I saw the paper by a radio astronomer from Chicago, John Carlstrom, together with his colleagues, reporting the results of interferometric observations of the effect in the direction of clusters at different redshifts from z=0.17 up to z=0.888 proving that clusters at high redshift have similar central "negative" brightness as clusters at much smaller redshifts.

It was impossible to even dream in 1969, when I first started to present talks about the effect, that today the South Pole Telescope, the Atacama Cosmology Telescope and the Planck spacecraft would discover more than a thousand previously unknown clusters of galaxies on the blank sky. It's a tremendous feeling to realize that the majority of these clusters have very high redshifts and the effect now permits us to look for the most massive clusters in our Universe. It's also very difficult to imagine that these clusters, discovered due to the effect, will be observed on the sky during the next billions of years. And there is the very big question: Will there still be astronomers on the Earth at such a distant point in time?

8. Epilogue

I remember how upset I was when, in the abstract of our article (Sunyaev and Zel'dovich 1970) Zel'dovich crossed out my words on the importance of observing the quasiperiodic scale-dependence of the amplitude of the CMB angular fluctuations. He wrote that the effect was very small and could hardly be observed. To calm me down he said that the physics of the phenomena described in the paper was beautiful, and the article needed to be published. I regret that Yakov Zel'dovich is not able to witness today how enormously rapid progress of detector technology allowed observing these, according to his words, "tiny and practically unobservable effects" with very high precision.

I am grateful to all the people who were working, designing new detectors of radiation, new telescopes, or spending long nights (with duration of half a year) at the South Pole Telescope. I am grateful to the people launching the excellent cosmology and high energy astrophysics spacecraft, sensitive to microwave radiation and X-rays, and designing and building the most sophisticated ground based optical and radiotelescopes. The great progress of solid state physics, cryogenic technology and development of the new types of detectors of radiation has enormously increased the sensitivity of these telescopes and spacecraft.

Science is not finished when one or the other theoretical prediction is confirmed by the observations. I am very glad that the effects which were predicted long ago are now helping astronomers to go ahead and investigate the properties of the dark matter and dark energy—substances of matter which fill our Universe (we know this from astrophysical observations using at least four independent methods). Of note, at least three of these methods (CMB acoustic peaks, the number counts of the clusters of galaxies at different redshifts and Baryonic Acoustic Oscillations) rely in some way on the effects discussed in this lecture. There is a hope that they will provide us with new information about the yet unknown laws of physics.

Yakov Zel'dovich invited me to do research in high energy astrophysics and cosmology. I accepted this invitation even though my department chief told me that astrophysics is a useless science. This decision later proved to be extremely lucky. Before the early 60s development of the world of astronomy was relatively slow. But in the middle of the 60s giant discoveries were being made practically every year. Among these great observational discoveries made during last 50 years were:

1. cosmic microwave background radiation (CMB), filling the whole Universe. Its angular distribution and frequency spectrum carries a lot of information about key properties of the Universe as a whole.

2. quasistellar radio sources (quasars) at cosmological distances. Today we know that these extremely bright sources of radiation in all spectral bands are accreting supermassive black holes in the nuclei of distant galaxies;

3. discovery of cosmological evolution of the powerful radiogalaxies and quasars;

4. radio pulsars which occurred to be rapidly rotating, strongly magnetized neutron stars;

5. accreting stellar mass black holes and neutron stars including X-ray bursters with quasiregular nuclear explosions on the surface of the neutron star;

6. gamma-ray bursts which for a few seconds appear much brighter in gamma-rays than the whole sky;

7. exoplanets, which opened the way to a better understanding of the origin and uniqueness of the planets in the Solar System;

8. evidence for the inflation of the Universe at it's very early stages;

9. evidence for the existence of dark energy and dark matter, which no one was able yet to detect in the ground based physical labs.

Astrophysicists of my and the following generations have been lucky because they entered our science at the great time of new and fascinating discoveries, opening new ways for further research. We know now a lot about our Universe and its properties and parameters. Nevertheless, many open questions remain and I hope that at least for the next 20-30 years my science—astrophysics and cosmology—will continue to glow.

Fig. 1 父のアリ・スニヤエフ（1912-1981）と母のサイーダ・キリディーワ(1917-2011)と一緒に（1945）
With my parents (1945): father Ali Sunyaev (1912-1981) and mother Saida Kilydeeva (1917-2011)

Fig. 2 恩師のヤーコフ・ゼルドヴィッチ先生と私（1970 年代初頭）
Academician Yakov Zel'dovich and Rashid Sunyaev in early 1970s

Fig. 3 ブラックホール降着円盤理論を研究していた 1970 年代半ば、ニコライ・シャクラ（左）と。二人はまだ若く、ブラックホールは非常に明るい物体になり得ることを証明しようと懸命に研究を続けていた。当時、ブラックホールと言えば「重力ポテンシャルが強すぎて光が逃げ出すことができないため、その姿を見ることはできないが…」というのが枕詞のようになっていた。

With Nick Shakura (left) in the middle of 1970s. We both were very young when we were working on the theory of disk accretion onto black holes – trying to demonstrate that black holes are able to become very bright objects. At that time every talk about black holes was started with the statement that they are completely invisible because their gravitational potential is so strong that light can not escape.

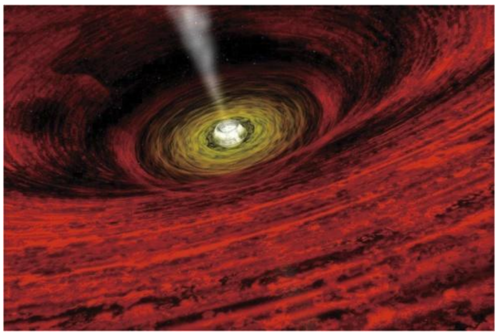

Fig. 4 降着円盤の内部領域（チャンドラ X 線天文衛星が捉えたイメージ）。円盤回転軸に沿ってジェット流が見える。

Inner regions of the accretion disk (artist impression. Courtesy Chandra X-Ray Observatory) including the jet along the disk rotation axis.

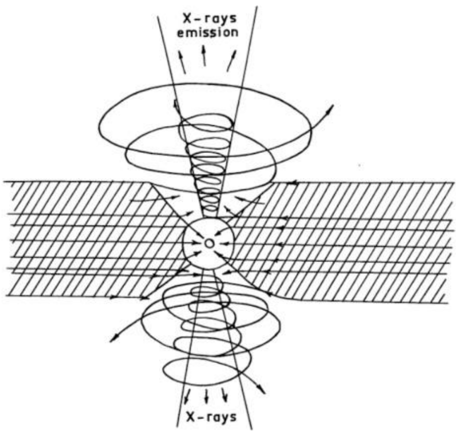

Fig. 5 超エディントン降着率で降着円盤中央領域から流出するガス（シャクラ、スニヤエフ、1973 年）

The outflow of gas from central regions of an accretion disk with supereddington accretion rate (Shakura, Sunyaev, 1973)

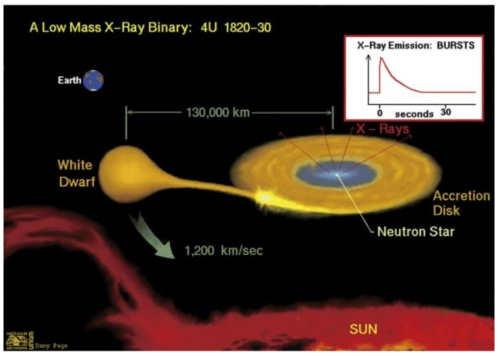

Fig. 6　小質量 X 線連星（イメージ、NASA 提供）

The low mass X-ray binary (artist impression, Courtesy NASA)

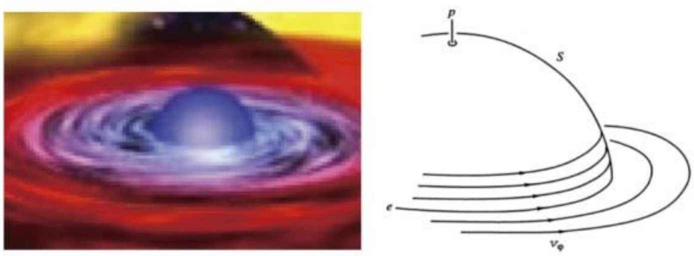

Fig. 7　磁場が弱い中性子星の周りの降着円盤の内部。左図は NASA 提供のイメージ。右図はイノガモフとスニヤエフの 1999 年の論文より。

The inner part of the accretion disk around the neutron star with a weak magnetic field. The left image is an artist impression, courtesy of NASA. The right image is from the paper by Inogamov and Sunyaev, 1999.

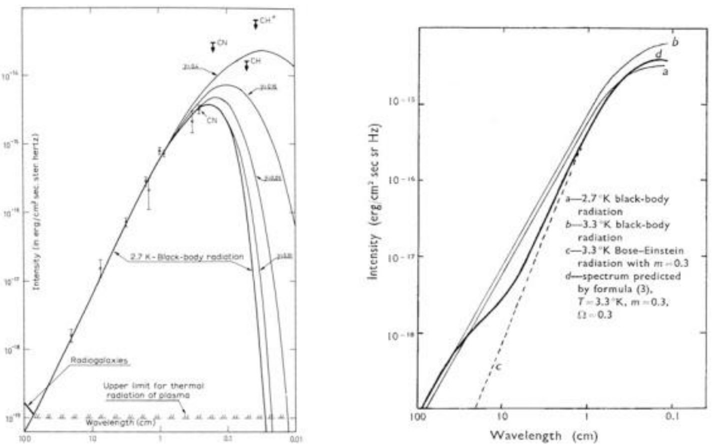

Fig. 8 宇宙マイクロ波背景放射のスペクトルの y-パラメータ変形を左に、μ-変形を右に示す（スニヤエフとゼルドヴィッチの 1970 年の論文より）

The y-parameter distortion of the CMBR spectrum is illustrated on the left, and the μ-distortion on the right. (from Sunyaev and Zel'dovich 1970)

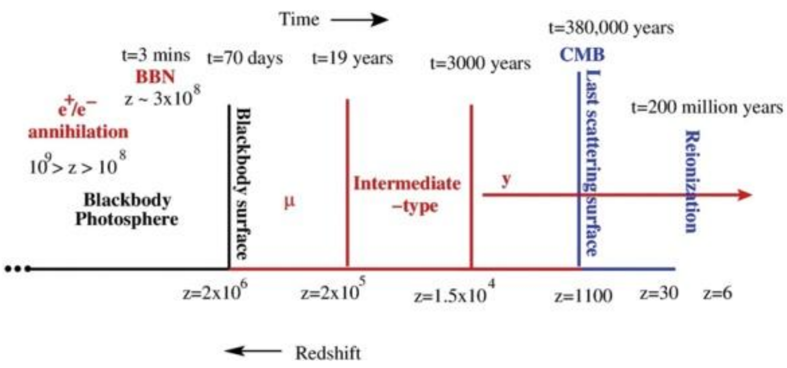

Fig. 9 宇宙マイクロ波背景放射のスペクトル変形の生成・進化に関連する重要な時期（カトリとスニヤエフの 2012 年の論文より）

Important epochs related to the creation and evolution of the CMB spectral distortions. From Khatry and Sunyaev, 2012.

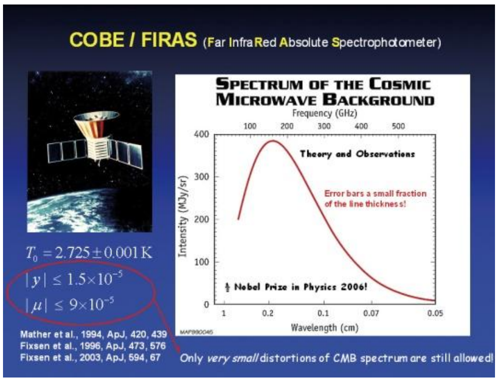

Fig. 10 COBE 宇宙船から計測した宇宙マイクロ波背景放射のスペクトル（NASA 提供）
The spectrum of the CMB measured by COBE spacecraft (Courtesy of NASA)

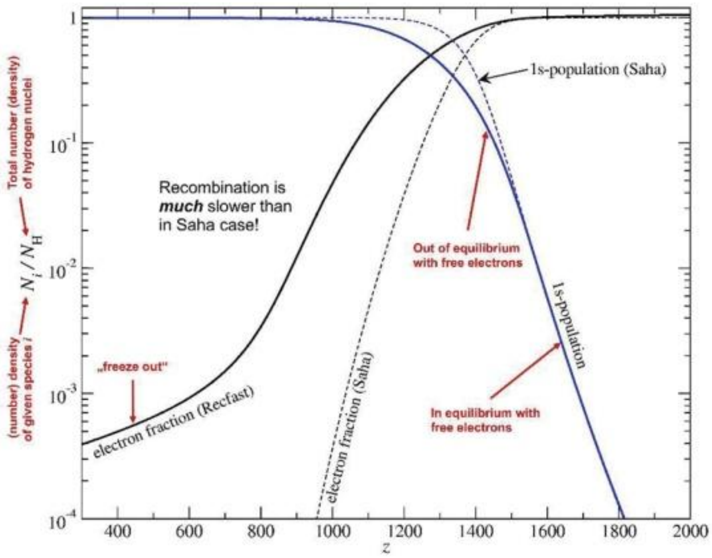

Fig. 11 サハのケースとの比較による、水素再結合の記録の差異。宇宙での水素再結合はライマンα共鳴やゆっくりとした 2s-1s 2 光子遷移が作り出す「隘路」により大幅に遅くなる（スニヤエフとシュルバの 2009 年の論文より）
Illustration of the difference in the hydrogen recombination history in comparison with the Saha case. The recombination of hydrogen in the Universe is strongly delayed due to the 'bottleneck' created in the Lyman α resonance and the slow 2s-1s two-photon transition (from R. Sunyaev, J. Chluba, 2009).

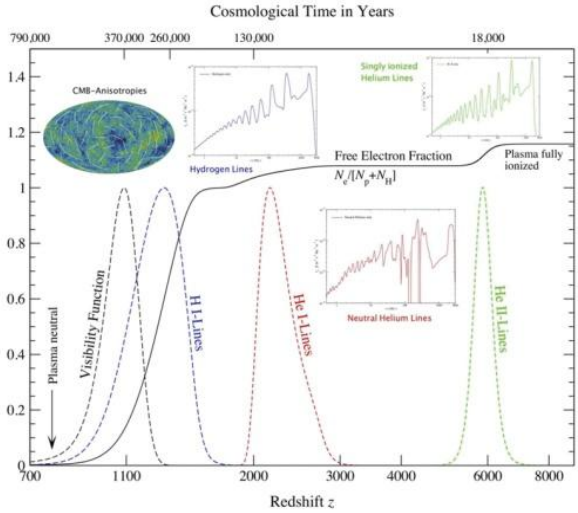

Fig. 12 宇宙のイオン化の経過（黒実曲線）と異なる宇宙マイクロ波背景放射の信号の起源（破線、嵌め込み図）

宇宙マイクロ波背景放射の温度における観測温度異方性が、z ~1089 付近のトムソン視感度関数の最大値近くで生成される一方、宇宙水素再結合スペクトル内の光子によって運ばれた直接的な情報は、それより少し前の時代からのものとなる。ヘリウムの二つの再結合に関わる光子は、さらに高い赤方偏移において放出された。宇宙再結合スペクトル内にこれらの信号の痕跡が見つかれば、ビッグバンから 13 万年後と 1 万 8 千年後の宇宙の姿を知ることができる。さらに、宇宙再結合放射は、宇宙再結合が終了する前に予期しない出来事（暗黒物質の粒子の対消滅によるエネルギー放出等）が起こったかどうかを知る術を与えてくれる。（スニヤエフとシュルバの 2009 年の論文より）

Ionization history of the Universe (solid black curve) and the origin of different CMB signals (dashed lines and inlays).

The observed temperature anisotropies in the CMB temperature are created close to the maximum of the Thomson visibility function around $z \sim 1089$, whereas the direct information carried by the photons in the cosmological hydrogen recombination spectrum is from slightly earlier times. The photons associated with the two recombinations of helium were released at even higher redshifts. Finding the traces of these signals in the cosmological recombination spectrum will therefore allow us to learn about the state of the Universe at ~ 130,000 yrs and ~ 18,000 yrs after the big bang. Furthermore, the cosmological recombination radiation may offer a way to tell if something unexpected (e.g. energy release due to annihilating dark matter particles) occurred before the end of cosmological recombination (from Sunyaev, Chluba, 2009)

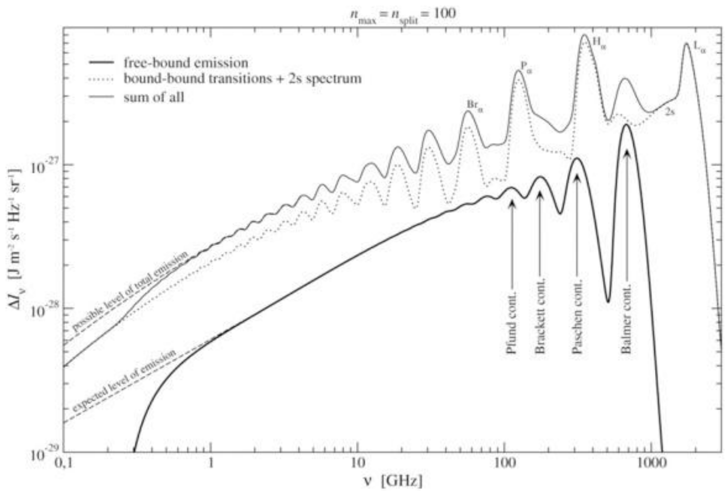

Fig. 13 自由‐束縛放射を含む水素再結合フルスペクトル（シュルバとスニヤエフが 2006 年に発見）。光学スペクトル帯から無線周波数まで、水素原子スペクトルが 1,500 回赤方偏移しているのが分かる。

The full hydrogen recombination spectrum including the free-bound emission found by J. Chluba and R. Sunyaev (2006). It represents hydrogen atom spectrum redshifted 1,500 times from optical spectral band to radiofrequences.

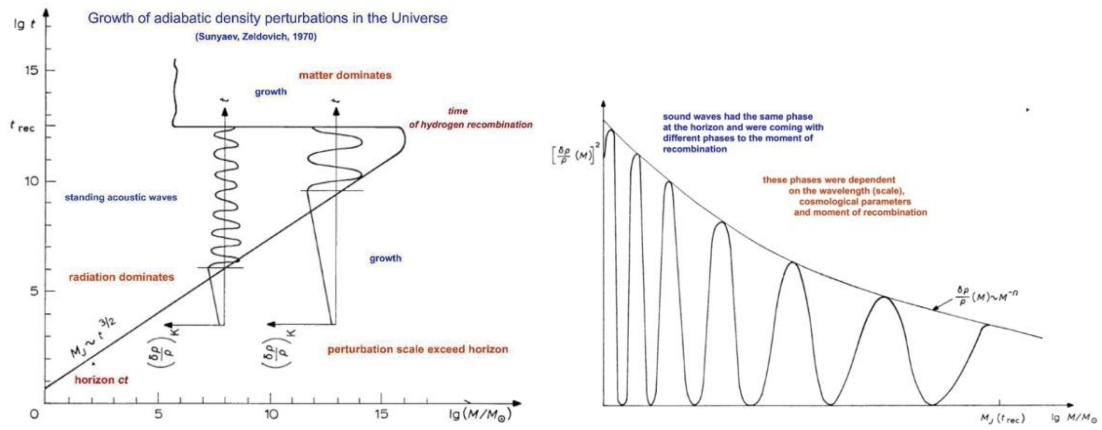

Fig. 14 宇宙で断熱密度摂動が成長する様子（スニヤエフとゼルドヴィッチが 1970 年頃に作成した図に手を加えたもの）

Illustration for the growth of adiabatic density perturbations in the Universe. The figure was adapted from Sunyaev & Zel'dovich (1970a).

Fig. 15　エイベル 2218 銀河団
Galaxy cluster Abell 2218.

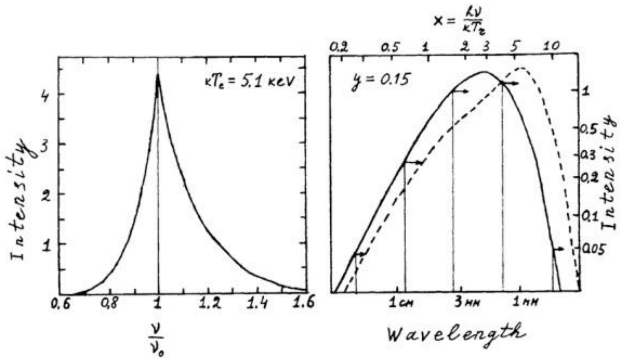

Fig. 16 kTe~5 KeV、平均速度 1/7 c 程度の高温のマクスウェル分布電子による放射の散乱。電子が動き回ることによるドップラー効果がもたらすスペクトル変化。初期の光子は周波数が低く、電子の温度も非常に高いため、重要なのはドップラー効果のみ。曲線の軌跡が広がり、v/c の 2 次効果によって実質的に高周波方向に動いている。その結果、強度はスペクトルのレイリー・ジーンズ部分で下降し、ウィーン部分で上昇している！（スニヤエフ、1980 年）

SCATTERING OF RADIATION BY HOT MAXWELLIAN ELECTRONS with kTe~ 5 KeV and average velocity of the order of 1/7 c. Spectral changes due to doppler-effect on moving electrons. Initial photons have low frequency, electrons are very hot, only Doppler effect is of importance. Line is broadened and effectively shifted toward higher frequencies due to second order effects in v/c. As a result – intensity drops in the Rayleigh-Jeans part of the spectrum and increases in the Wien part ! (from Sunyaev, 1980)

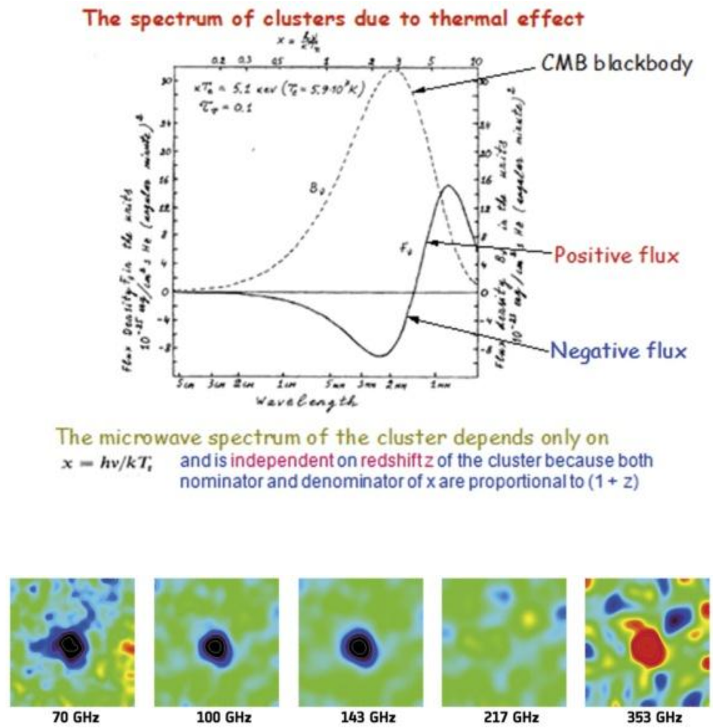

Fig. 17 上プロット：リッチな銀河団方向における宇宙マイクロ波背景放射のスペクトルの変化（予想図、スニヤエフの 1980 年論文より）。下プロット：銀河団 A2319 のプランク衛星の観測データ（ESA 記者会見から）。プランク衛星の検波器の最初の三つの低周波数チャンネルにマイナス信号が観測されている。217GHz 近く（1.5mm 近くの波長）の信号は弱すぎて観測できない。予想通り、銀河団からの信号は高周波チャンネルではポジティブとなっている（ESA 記者会見から）

Upper plot: the change of the CMB spectrum in the direction to the rich cluster of galaxies (prediction, from Sunyaev, 1980). Lower plot: Planck spacecraft observational data for the cluster A2319 (ESA press-conference). Negative signal is observed in the first three low frequency channels of the Planck spacecraft detectors. In the vicinity of 217 GHz (wavelength close to 1.5 mm) signal is too weak to be observed. The signal from the cluster is positive in the high frequency channel, exactly as it was predicted. (ESA press-conference)

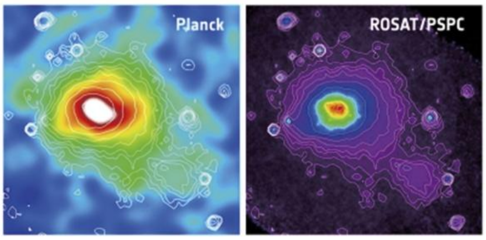

Fig. 18 マイクロ波スペクトル帯（左：大変大きな意味を持つネガティブ信号の検知。プランク衛星観測データ）および X 線（ローザット衛星観測データ）内のかみのけ座銀河団。ESA 記者会見より

Coma cluster of galaxies in microwave spectral band (left; Very high significance detection of the negative signal. Planck spacecraft data) and in X-Rays (ROSAT spacecraft). ESA press-conference.