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Scientific Reminiscences

Convection, helioseismology and solar energy: personal reminiscence*

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Abstract This article is a brief history of my life from childhood and describes how I became interested in astronomy. Starting from researches using radiative transfer as a main tool, I gradually expanded my research field to hydrodynamics (particularly convection, turbulence, pulsation, waves and helioseismology), magnetohydrodynamics and chaotic systems. My recent interest is to develop a sustainable society using solar energy.

Key words: convection — helioseismology — Zeeman effect

1 CHILDHOOD

To begin with, as memory deteriorates as one ages, please forgive me if I miss important events or names in the following text. I had not tried (nor was I able) to recall all of my research topics or collaborators.

I was born in October 1925 in Urawa city, Saitama prefecture which is located north of Tokyo. My father was a teacher of physics and chemistry at Saitama Women's Normal School when I entered elementary school there. (The school system at that time was six years in elementary school, four to five years in junior high school, three years in senior high school and in university.) When I was a third grader or so, my uncle taught the game of 'go' to me and my two elder brothers, and I continue enjoying games of go till now.

As my father was promoted to higher positions, the family moved to several places, ending up at Hiwasa in Tokushima prefecture, Shikoku Island, when I was probably a fifth grader. Hiwasa is now famous for its beach where turtles come up from the sea and lay eggs in the May-August period and it is designated as a natural monument. Also Hiwasa hosts Yakuoji temple, the 23rd of 88 Shikoku pilgrimage temples of Shingon Buddism. People in Tokushima are known for warm hospitality but I could not understand what they spoke in a local dialect. Children establish friendships after physical fights, and this was the case for me. In order to have some advantages over the fellows, I practiced kendo (Japanese fencing using a sword made of bamboo) very hard. I also learned soroban (Japanese abacus) and the Heart Sutra (BanRuoXinJing in Chinese), among others, which I still remember.

When I was a third grader in junior high school, the family left Shikoku and moved to Otsuki city in Yamanashi prefecture. Usually one spent five years in junior high school before proceeding

* This article is based on an interview with Professor Unno on 2013 December 21 at his home by Yoji Osaki and Takashi Sakurai, and was drafted by Sakurai (*sakurai@solar.mtk.nao.ac.jp*).

to senior high school at that time. I graduated junior high school one year earlier and took the entrance examination for Matsumoto senior high school in Matsumoto city, Nagano prefecture. Maybe because I liked and was good at mathematics, fortunately I was admitted there. Among 40 or so classmates from the high school, only two graduated from junior high school in the fourth year. In high school I liked physics because of a superb teacher, but I lost interest in chemistry because my chemistry teacher was a very strange person. My passion, however, was not directed toward study but to kendo. I became 2-dan (second grade), and had never lost matches during high school. As the war became serious, the students were forced to work at military factories for almost one year, and had to graduate from there in only two and a half years, cutting short the normal three-year course.

2 UNIVERSITY DURING WAR

As many high schools shortened their term in order to supply a labor force during the war time, it was hard for universities to carry out the entrance examination at a fixed time. I wanted to continue learning physics at a university and decided to try the University of Tokyo. However, the University of Tokyo decided not to carry out the entrance examination for the year 1944. Instead they announced that they would take students based on their achievement record in high school. As I was mostly committed to kendo and my academic grades were not so impressive, and the brightest students generally headed to the department of physics, I gave up the physics department and picked the astronomy department. At that time the astronomy department was not so popular; its capacity was five students per year but had never filled this capacity.

My application was fortunately successful, but later I found out that there were five freshmen in the astronomy department, unusually, and it seemed that they had all speculated like I did. My classmates (Fig. 1) were Goro Ishida who was the son of a famous seaweed dealer in Ueno, downtown Tokyo, and later became an astronomer and worked at the Tokyo Astronomical Observatory; Naoaki Ohwaki who later got a job at Tokyo Gakugei University and taught astronomy there; Kinji Miwa and Ken Matsuda. Miwa was full of curiosity at many things and later became a medical doctor. Matsuda, who was good at playing the piano, had health problems due to poor nutrition and, although he managed to graduate from the university six years later than the other classmates, died prematurely. I would say that this class was made of interesting persons, contrary to the physics students who might be smart but childish, except possibly for Leo Esaki who won the Nobel Prize in physics in 1973. Naoshi Fukushima was a freshman in the geophysics department; he later became a professor at the University of Tokyo and studied magnetospheric physics.

The astronomy department in October 1944 when I entered the university consisted of two full professors (K. Sekiguchi and Y. Hagihara), two associate professors (N. Fukumi and M. Kaburaki) and three assistant professors (Y. Fujita, T. Hatanaka and M. Furuhata). Professor Yusuke Hagihara was my supervisor. The department's building was located at Azabu, while lectures on physics and mathematics were given in the main Hongo campus. Hagihara once studied astronomy at Cambridge under H. F. Baker and A. S. Eddington, and although his expertise was celestial mechanics, he also taught modern astrophysics using many articles from Monthly Notices of the Royal Astronomical Society (MNRAS). On some occasions when I was a sophomore, he said that he might die in this war period so he tried to teach everything he learned to young students, and gave lectures from morning till night for over ten days or so. The students were exhausted at the end of the day, but were impressed by his enthusiasm and they gradually became confident that basic knowledge and skills had developed in them.

Tokyo was attacked almost every day by American B-29 bombers, and the department professors decided to evacuate the class to a distant place in Suwa area from April 1945. Suwa was close to Matsumoto, a place I was familiar with. Y. Fujita (then associate professor) and T. Hatanaka (then lecturer) accompanied the students, and other professors visited the place where the evacuation was located from time to time to give courses. In order to secure food, some students including myself

Fig. 1 *Left*: Freshmen in the 1944 astronomy class at the University of Tokyo in front of the department building at Azabu; Ishida, Miwa, Ohwaki and Unno. Dr. Y. Fujita is on the right (reproduced from "Kamisuwa Diary," Ryuho Shobo, Ltd., 1993). *Right*: The author in 1953 in a group photo taken at the 75th anniversary of Tokyo Astronomical Observatory, the University of Tokyo (reproduced from "100 Years of Tokyo Astronomical Observatory," 1978).

worked at a nearby village for the Land Survey Department, performing ephemeris calculations. We heard the radio broadcast of Emperor Hirohito on August 15 accepting the Potsdam Declaration. We returned to Suwa and to Hongo, Tokyo, in October. The astronomy building at Azabu and all the observing instruments and books had been burned during the massive firebombing of downtown Tokyo on May 25. These were the days when no one had clear vision of what the future would be.

3 EARLY SCIENTIFIC CAREER

I graduated from the University of Tokyo in 1947 and proceeded to the graduate course. For five years in the graduate course, I was appointed as a special research student and received a minimal amount of salary. Life was still difficult and I stayed at the residence of Dr. Hatanaka at Tokyo Astronomical Observatory (located at Mitaka) with some of my fellow students. We also grew sweet potatoes on the observatory's campus.

My first research work was on planetary nebulae under the supervision of Hagihara and Hatanaka (Unno 1950, 1952a,b,c; Unno & Takakubo 1952). A planetary nebula is an expanding shell of gas ejected from a star in its last stage of evolution with a speed of roughly 20 km s^{-1}. Its central star, with a temperature of $10^{4.5} - 10^5$ K, emits strong UV radiation in the He II 304 Å line which is believed to drive the gas. A simple calculation of the radiation pressure on a static gas shows that it is too strong and would drive the gas to a speed exceeding a thousand km s^{-1}. The key is the expanding motion of the gas in which an atom would absorb and emit photons at different wavelengths. This is called Zanstra's mechanism and explains the observed expansion speed of 20 km s^{-1}. Maybe these works were appreciated by the professors, and I was appointed as an associate professor at Tokyo Astronomical Observatory, the University of Tokyo, in 1952 just before finishing the graduate course. Although my first paper (Unno 1950) was more like an exercise ordered by my supervisors, I was able to digest the style of Hagihara and Hatanaka, and in my doctoral thesis (Unno 1955) I even competed with such big names as D. H. Menzel and L. H. Aller.

One year later I moved to the astronomy department of the University of Tokyo in Hongo, downtown Tokyo, and stayed there until my retirement in 1986.

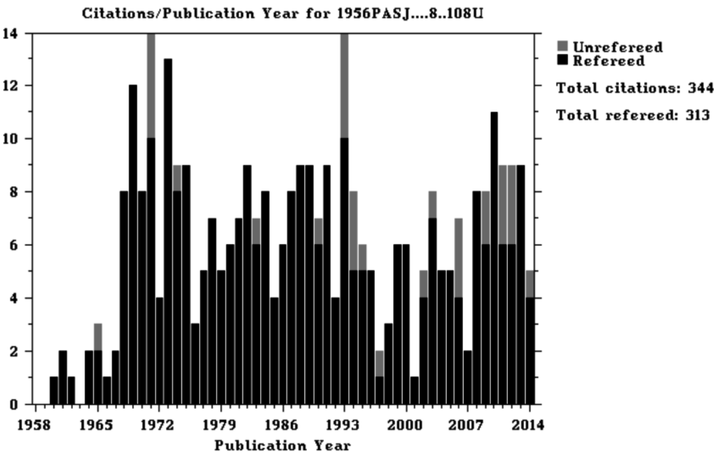

Fig. 2 Citation record of Unno (1956) on the Zeeman effect, according to ADS.

4 ZEEMAN EFFECT

My paper with the largest number of citations (Fig. 2) is on the Zeeman effect of normal triplets (Unno 1956). The popular formula used before that time was due to Seares (1913) which did not consider line formation by radiative transfer. Although the formula I derived was limited to normal triplets and to a simple case in which magneto-optical effects can be neglected, I thought that it would be important to provide a tool to investigate the three-dimensional structure of solar magnetic fields using the observed polarization spectra. Keizo Nishi who was in Munich in 1959 was told by his German colleagues that Unno's model was beautiful but useless. His patriotism seemed to be ignited, and he applied my formula to his observations of sunspot spectra obtained at the tower telescope at Mitaka (Nishi 1962). Unno & Kato (1965) and Kodaira & Unno (1969) analyzed the magnetic field on a star using this formula. Stepanov (1961) treated the same problem with a different approach and for general Zeeman splitting patterns, and Rachkovsky (1962) derived the formula with magneto-optical effects included. I am pleased to know that the standard data analysis method adopted for the Spectro-Polarimeter onboard the Japanese *Hinode* satellite is based on this method (Orozco Suárez et al. 2007).

5 LIGHTHILL MECHANISM

The heating mechanism of the chromosphere and the corona was (and still is) an unresolved problem. Lighthill (1952; 1954) formulated the generation of sound waves from turbulent fluid. In the case of isotropic turbulence, the leading term generating the power of emitted sound waves is due to the quadrupole moment of the motion and is proportional to the 8th power of the velocity of turbulence. In order to apply this theory to the solar atmosphere, Unno and Kawabata (1955) estimated the velocity of turbulence just below the photosphere by using the model for the convection zone by Vitense (1953). Unno & Kato (1962) and Kato (1963) extended this theory to gravitationally stratified atmospheres and found that the dipole term is as important as the quadrupole term. Unno (1966) more concisely summarized the results; the sound waves are generated by the monopole, dipole and quadrupole contributions. If the size of turbulent eddies l_0 is small ($l_0 < 2(u_0/c)H$, c is the sound speed, H is the scale height and u_0 is the characteristic value of turbulent velocity), the quadrupole contribution dominates as in isotropic turbulence. If l_0 is large ($l_0 > 2(u_0/c)H$), the effect of stratification is significant and the monopole and dipole contributions can be larger than the quadrupole contribution.

In the 1970s it had become clear that the corona is more intensely heated above active regions, and the magnetic field must play an essential role in the heating mechanism (Vaiana & Rosner 1978). Therefore the theories we developed might have become obsolete. On the other hand, *Hinode* recently discovered a variety of waves in the solar atmosphere (Okamoto et al. 2007; Fujimura & Tsuneta 2009). It would still be interesting to study the role waves play in the solar atmosphere.

6 EXPERIENCES OUTSIDE JAPAN

6.1 Princeton

My first visit outside Japan was to Princeton. Hagihara and Hatanaka recommended me for the Fullbright fellowship, and in 1956 I sailed on Hikawa-Maru to Seattle and then took a train to the East Coast. It was only ten years after the end of the war and I knew that my host, Martin Schwarzschild, was forced to immigrate to America because of persecution by the Nazis. Therefore I felt uneasy before I met him. Martin, as I used to call him since then, was a gentleman with big round eyes and a soft smile, which relieved my fear. He asked me what I would like to study, and I said that I wanted to expand my research to new fields beyond radiative transfer. I recalled that once he had introduced the concept of running waves in the context of a 90° phase shift between the radius and luminosity variations of Cepheid variables under non-adiabatic pulsation. After discussing about this, he suggested me to study the dynamical coupling (in addition to the thermal one) between convection and pulsation in stars. This was the start of my researches on stellar pulsation and convection. First I tackled anisotropy in convective motions (horizontal vs. vertical motions) in the solar surface layer (Unno 1957).

Martin Schwarzschild was famous for his work on the internal structure and evolution of stars. He also carried out a balloon experiment to observe solar granulation with high spatial resolution (Schwarzschild 1959), and Robert Howard was a student at Princeton at that time. However, Princeton University Observatory was mostly for theoretical research in spite of its name. I also noticed a tight competition among young researchers. They worked very hard to be recognized by their supervisors, and they were trying to publish as much as possible. Even native English speakers revised their manuscripts many times in order to make them better, which was not my option considering my command in English, though. Aside from language, however, I felt no difference in research capability between myself and them; the astronomy I inherited from Hagihara and Hatanaka was good enough for me to be competitive in the United States.

6.2 Michigan

I wanted to stay at Princeton for one more year but it turned out to be impossible. I was introduced to a new host, Leo Goldberg, and I moved to the University of Michigan. They were operating a solar observatory, the McMath-Hulbert Observatory, which was famous for the atlas of Sun's infrared spectra (Mohler et al. 1950). I therefore started working in solar physics. First I applied Goldberg's (1958) multiplet method to the spectroscopic data obtained at McMath-Hulbert and derived height variations of turbulent velocity in the photosphere (Unno 1959a) and in the chromosphere (Unno 1959b). In Goldberg et al. (1960) we studied the center-to-limb variations of turbulent velocity.

I remember that they chatted about the white-light flare which I observed with the solar tower telescope at Mitaka, Tokyo (Notsuki et al. 1956), without knowing that I observed it. Edward Spiegel was among the students there, with whom I had co-authored several papers later (Spiegel & Unno (1962) on convection; Unno & Spiegel (1966) on radiative transfer). He once said that my work at Michigan was better than that at Princeton.

After I returned to Tokyo from the United States, I organized a small group for the study of convection and turbulence. The members were two students of the astronomy department (Shoji Kato and Mitsugu Makita), myself and Sinzi Kuwabara of the Aeronautical Research Institute. We had weekly seminars, which led to two papers on the stability of polytropic atmospheres (Unno et al. 1960; Kato & Unno 1960). In this period I was stressing to my collaborators that the theory of turbulence would gain more importance among astrophysical applications. In Unno (1962) I derived the power spectrum of turbulent motion for length scales of large energy-carrying eddies, which was conveniently defined by the Reynolds number of about 30 in the eddy viscosity formula.

6.3 Munich

My first visit to Europe was in 1963–1965 to Munich, at the Max-Planck Institut für Astrophysik. My host, Rudolf Kippenhahn, moved from Göttingen to Munich in 1959; his famous paper on prominence magnetic fields (Kippenhahn & Schlüter 1957) was written in Göttingen. In Munich I continued my study on convection (Unno 1965a) and gradually shifted my stress toward stellar pulsation (Unno 1965b) in collaboration with Kippenhahn and Alfred Weigert.

It was also around this time that magnetohydrodynamics (MHD) emerged as a new research field. H. Alfvén had just published his book (Alfvén & Fälthammar 1963), and I saw him in a conference. With his very characteristic pronunciation of his name with stress on "vee," I became interested in MHD. In the 1970s I wrote several papers on solar MHD phenomena with my French collaborators (Unno et al. 1974, 1981).

Another major incident during my stay in Munich was the unexpected death of my mentor, Takeo Hatanaka, in November 1963 at the age of 49. He had been working on research (he is the founder of radio astronomy in Japan), making science policy at the government level, and also working on popularization of astronomy. He was the Carl Sagan of his time in Japan.

7 PASJ AND THE HAYASHI PHASE

From 1959 to 1962 I served as the Associate Editor of the Publications of the Astronomical Society of Japan (PASJ). The Managing Editor was Y. Fujita (1959–1960) and T. Hatanaka (1961–1962). (Much later in 1969–1976 I served as Managing Editor.) As the number of submissions was not so large, I read all the manuscripts. As PASJ was not as widely known and recognized as Astrophysical Journal (ApJ) or MNRAS, I was keen to attract good papers. Then, I heard that Chushiro Hayashi of Kyoto University had given a talk in a symposium about the evolutional track of pre-main-sequence stars and was praised by Martin Schwarzschild. I asked Dr. Hayashi to submit this result to PASJ, and PASJ was able to publish this world-renowned paper on the "Hayashi phase" (Hayashi 1961). I was familiar with this topic because a student of mine (who happened to also be Mr. Hayashi) had been studying the same problem, but he published his work much later (M. Hayashi 1965).

8 HELIOSEISMOLOGY

In 1967 I sent Yoji Osaki to Columbia University in New York. His host was Norman Baker, who once worked with Kippenhahn, and I recommended Osaki through him to Baker. There Osaki started research on non-radial oscillations of stars, partly stimulated by W. Dziembowski who was also visiting there. Until then the studies on stellar oscillations were mostly limited to radial pulsation. After returning to Japan, he supervised Hiroyasu Ando and published a paper on the interpretation of five-minute oscillations in the Sun (Ando & Osaki 1975). The predicted k–ω diagram was observationally confirmed by Deubner (1975), and a slight discrepancy between them led to improving the model of the solar interior. This was the beginning of modeling the solar interior by inversion.

During this period, I was interested in possible destabilization of the g-mode oscillation in the core of the Sun by the presence of a concentration of ^{3}He, which might explain the deficit in the

Fig. 3 A group photo of the members (not all of them) of the astronomy department at the University of Tokyo in 1978, on the rooftop of the astronomy building. From left to right: W. Unno (professor), T. Sakurai, K. Uzawa (secretary), M. Takada, S. Tsuneta, A. Texeira (intern student), M. Hamabe, T. Takakura (professor), T. Fukushima, H. Shibahashi, M. Iye, T. Watanabe, T. Hasegawa, I. Hachisu, T. Motoki (administrator), G. Hori (professor), W. Tanaka (research associate) and H. Kimura (visiting researcher). The top-right inset shows Y. Osaki and K. Kodaira (associate professors). The names without a job designation were all graduate students.

observed neutrino flux (Unno 1975). After Hiromoto Shibahashi joined the group, a more detailed numerical analysis on the stability was made (Shibahashi et al. 1975). They concluded that the present Sun will not show instability. As the recent neutrino observations show, basically there is no discrepancy between theoretical expectation and the observed neutrino flux when all the neutrino species are detected and combined (Haxton et al. 2013).

I predicted that helio and asteroseismology would become a mature research field soon, and proposed to write together an English textbook on them to my younger collaborators Osaki, Ando and Shibahashi. Initially they were rather reluctant considering the energy one must put in to write a book in English, and also they were afraid that the book might not be read by many. I obtained a grant that supported the publication of the book, and "Nonradial Oscillations of Stars" was put into print (Unno et al. 1979). I am proud that my prediction was correct, and the book was well received as a standard textbook for nonradial oscillations of the Sun and stars. In 1989 the second, expanded edition was published (Unno et al. 1989).

Since the mid 1960s I had a weekly seminar at the astronomy department (Fig. 3) every Monday afternoon with my young collaborators and students, and had listened to their talks. The topics discussed covered a wide variety; although the central topic was theoretical astrophysics, talks on observational astronomy were also accepted. I am not sure whether I have given them good enough advice; the students grew up almost on their own. I am happy to say that many of them have shown marvelous research activities and supervised many students who are second, third and even fourth generation students of mine.

9 BUILDING UP TIES

My collaboration with scientists in Asian countries began around 1980. In 1978 I visited Cai-Pin Liu and her husband, Hiroshi Kimura, who had both graduated from the astronomy department of the University of Tokyo and emigrated to China. They were based at Purple Mountain Observatory, Nanjing, and I gave seminars there and in Beijing. My lectures were translated to Chinese by Liu and Kimura for other Chinese attendees. There I met Da-Run Xiong who had been studying turbulent convection with his own theoretical framework (nonlocal mixing-length theory). I started collaboration with him and produced several papers on the convection zone of the Sun (Unno et al. 1985; Xiong et al. 1991, 1992).

In 1984 I visited India. My collaborator was N. Rudraiah of Central College, Bangalore University. His style was more toward mathematics, and we collaborated on the theory of nonlinear magnetoconvection (Rudraiah et al. 1985a,b). I stayed there for almost two months, with a cook assigned exclusively to me. Although the working environment in the university was calm and comfortable, I was often embarrassed by chaotic situations with racial and religious conflicts in Indian society. It looked like a mixture of hope and confusion.

I visited Seoul, Korea and the surrounding area, in 1985, and was impressed by its rapid economic growth. Unfortunately I was not able to initiate collaborative research with Korean scientists. On the other hand I have written a beginner's textbook (1993) on how to learn the Korean language; my point was to utilize Chinese characters more efficiently rather than relying only on Hangul characters which are phonetic.

10 RECENT ACTIVITIES

After my retirement from the University of Tokyo in 1986 at the age of 60, I moved to Kinki University in Osaka, a big private university. My interest in this period was initially on chaotic systems. With one of my students, Kenji Urata, we studied chaos in convection and other astronomical phenomena (Urata 1987; Unno et al. 1990). In this process I became more and more aware of the vulnerability of our society and natural environment. I started seriously considering natural energy and development of a self-sustaining society. I spent about ten years at Kinki University. After retirement from there, I set up a research forum called Senjikan Institute of Future Study, with several active members. In 2003 I joined Tokyo Freedom Academy, a non-profit organization, and have been serving as its president.

Last October I became 88 years old (Fig. 4). My recent interest is on concentrated solar power converters. In an ordinary solar panel, the amount of extractable energy is nearly the same as the production cost of solar cells and there is no real gain. If one uses light-collecting optics to increase the energy density of light by sixteen times, by the Stefan-Boltzmann law one can raise the temperature by a factor of two, namely up to about 600 K $\approx$ 300°C. This heat can be stored in material with a large specific heat such as molten salt, and can be used later, for example during night, for electric power generation or in other processes. The light-feed optics can be a coelostat mirror which may reflect the light beam vertically down to a container of molten salt. The optical thickness of the molten salt should be adjusted so that the incoming energy is completely absorbed when arriving at the bottom of the container. An example of such a "solar pond" has been formulated (Unno & Taga 1993).

As Stephen Hawking predicted, mankind may become extinct in one hundred years due to their own civilization. We must seriously consider efficient usage of energy, and I hope that young people are interested in such challenges.

Fig. 4 At the celebration of my 88th birthday in October 2013.

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