J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 100–106

The Legacy of Masahiro Wakatani

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(Received: 18 February 2004 / Accepted: 7 April 2004)

Abstract

As a memorial to Masahiro Wakatani, late professor of plasma physics at Kyoto University, a review is given of his legacy of achievements in scientific research, international collaborations, university administration, student guidance, and personal life.

Keywords:

Hasegawa-Wakatani equation, turbulent transport, helical system stability, drift wave, reduced MHD equation

1. Introduction

The international community of fusion plasma physicists was deeply saddened by the unexpected loss of one of its most respected members, Prof. Masahiro Wakatani, of Kyoto University, who died from a cerebral hemorrhage on 9 January 2003. This paper, based on a talk [1] presented during a special memorial session at the 13th International Toki Conference (9-12 December 2003), is offered as a tribute in his memory.

Professor Wakatani had a brilliant career as a scientific researcher, international collaborator, university leader, and teacher. In this paper, after providing a brief biographical sketch, we will describe each of these aspects of his very significant legacy and also offer some personal comments about him.

2. Capsule biography

Here we briefly list some selected biographical details and important dates in his career. This list will serve as a chronological framework for the description of his many accomplishments.

He was born on 15 May 1945, in Osaka, Japan.

He attended Kyoto University for his undergraduate and graduate education. He graduated with a B.Sc. degree (1968) and a Master's degree (1970) in nuclear engineering. He then obtained a Dr.Eng. degree in electrical engineering (1973) with a thesis entitled "Magnetohydrodynamic Equilibrium and Stability of Toroidal Pinches" under the guidance of his thesis advisor, Prof. Ryohei Itatani.

After graduation, he was first employed at the Japan Atomic Energy Research Institute as a Research Associate in the Division of Thermonuclear Research (1973-1976). Subsequently he went to the Institute of Plasma Physics, Nagoya University, as a Research Associate in the Theory Division (1976-1978).

In 1978 he joined the Plasma Physics Laboratory at Kyoto University as an Associate Professor. He was promoted to full Professor in 1985. In 1996 he became a Professor in the Department of Fundamental Energy Science and the Department of Nuclear Engineering.

He was elected a Fellow of the American Physical Society in 1990.

He died on 9 January 2003. Two obituaries about him have been published [2,3].

3. Legacy of innovative research

Without question Wakatani was one of the very best theoretical and computational plasma physicists in the world. He published many influential papers. His creative and original work on nonlinear MHD, drift wave instabilities, stellarator confinement, and ion-temperature-gradient mode dynamics is famous. Here we provide a brief description of his major contributions to several areas of theoretical plasma physics research.

According to Prof. Tokuhiro Obiki's obituary [2], Wakatani's scientific talent and brilliance were already obvious in his student days. He had the highest marks of any student ever in nuclear engineering. For his Ph.D. thesis, he carried out the first application of neoclassical theory to the toroidal pinch confinement device. He used the neoclassical theory of Roald Sagdeev and Alec Galeev, which was brand new at that time, to calculate the collisional diffusion coefficients in a toroidal pinch [4].

After graduation, he continued his work on stability and transport, switching his attention first to the tokamak device, which had much better confinement than the toroidal pinch, and (when he joined the faculty at Kyoto University) also to

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helical confinement devices, especially the Heliotron/torsatron line. A major scientific accomplishment, published in the year that he moved back to Kyoto, was his derivation of reduced MHD equations for helical systems [5]. These equations were derived by means of an averaging approach, based on the "stellarator expansion technique." They are a simplified version of the full MHD equations, but yet retain the essential helical physics and – quite importantly – are amenable to nonlinear numerical simulations. These reduced equations are still today the popular standard model, used worldwide for MHD analysis and machine design.

Perusal of his extensive list of publications leads to an appreciation of how much work he did on analyzing Heliotron experimental results. He was a co-author on many papers dealing with pellet injection, heating, equilibrium, stability, transport and confinement, etc., in Heliotron experiments [6]. Furthermore, he, with his students, carried out studies of a Helias-Heliac hybrid stellarator [7] and helped with the design of the Heliotron-J device, which was subsequently constructed and is now operating at Kyoto University. Heliotron-J is a helical axis device, based on the quasi-isodynamic (i.e., quasi-omnigenous) optimization approach to the helical-axis Heliotron line.

In the early 1980's, shortly after the launch of the U.S.-Japan fusion theory exchange activities (to be described in Sec. 4), Wakatani began to study anomalous transport due to turbulence arising from micro-instabilities, a major obstacle to improved plasma confinement. In 1983, working with Dr. Akira Hasegawa (then at Bell Lab), he derived a set of nonlinear evolution equations that describe strong turbulence caused by resistive drift-wave instability at the edge of a plasma [8]. Using these equations, they showed the existence of an inverse cascade of energy from short to long wavelengths in plasma turbulence. They also found a prototype mechanism for generating large-scale poloidal flow structures (e.g., zonal flows and streamers in tokamaks).

These "Hasegawa-Wakatani equations" for nonlinear drift waves have become extremely well known and hence deserve special notice in any description of Wakatani's accomplishments. We speculate that perhaps because he lived in the ancient cultural region of Kyoto and Nara, he liked theories that were simple, orderly, and yet elegant, like a Zen garden. Thus, the Hasegawa-Wakatani theory created a highly simplified formulation of the drift wave equations, in which two coupled nonlinear partial differential equations provide a powerful paradigm for studying the transition from collisional drift wave turbulence to collisionless drift waves, all in terms of a single parameter. These equations immediately became very popular and have been extensively used by many other researchers. One example is the use of the Hasegawa-Wakatani equations by theorists and applied mathematicians to test closure models for describing turbulence.

Wakatani went on to write nine more papers with Hasegawa, two of which were also published in *Physical Review Letters*. The results of one of these papers [9], a study of the self-organization of electrostatic turbulence, have been used in some recent experimental work [10] to explain shear flow-induced transport barriers.

Wakatani was clearly a world leader in the studies of drift wave and resistive-g mode turbulence. He was unique in that he not only developed a simple paradigm model (namely, the two-dimensional Hasegawa-Wakatani equations with one parameter), but also constructed technically complete models for three-dimensional helical systems. He gained an international reputation for his work on drift wave instabilities in toroidally confined plasmas. His studies of anomalous transport induced by ion temperature gradient (ITG) and electron temperature gradient (ETG) instabilities are well known. One of us had the privilege of co-authoring a series of ITG and ETG papers with Wakatani and also several of his students (especially Dr. Hideo Sugama) [11].

Wakatani and his students skillfully used large-scale computing for attacking complex systems. A rather recent example was his work on simulating the dangerous plasma transport due to electron-temperature-gradient turbulence in reversed-shear, nearly collisionless toroidal systems with a record number of representative electrons per cell in a self-consistent field [12].

In addition to doing original research, he somehow found time to publish five books. He co-authored two textbooks with Prof. Kyoji Nishikawa. The first, *Physics of Continuous Fluids* [13], unfortunately available only in Japanese, covers material from low-temperature quantum fluids to high-temperature plasmas. Their other jointly written book, *Plasma Physics: Basic Theory with Fusion Applications* [14], was used by us as a graduate-level text at the University of Texas and has been reprinted in three editions so far. Two of Wakatani's other books were related to U.S.-Japan exchange activities. One was a conference proceedings, *U.S.-Japan Workshop on Ion Temperature Gradient-Driven Turbulent Transport, Austin, TX, 1993* [15]. Another arose out a series of U.S.-Japan workshops, which he helped to organize, and scientific exchange visits, in which he participated (mostly with scientists at New York University), concerning the development of the BETA equilibrium, stability, and transport codes and their application for stellarator design [16]. Unquestionably his magnum opus was his final book, *Stellarator and Heliotron Devices* [17]. This text is extremely well written, providing both physical pictures as well as detailed descriptions, and covering not only MHD and resistive MHD physics but also drift wave physics (very important for helical plasmas) – in short, a veritable "bible" of stellarator theory.

An impressive feature of Wakatani's research is that it combined deep physics insight and development of fundamental new theory, with applications to urgent, real-life problems. We think that the reason for this dual style was his motivation to achieve the ultimate goal of abundant, clean fusion energy for the benefit of world society. He sought to work toward this goal by the three means of predictive capability for simulations and theory, the ability to design and control plasma parameters and profiles, and critical experimentation.

4. Legacy of international collaborations

Wakatani was an absolute pillar of support for U.S.-Japan collaboration activities. In particular, for 22 years he provided valuable service to the Joint Institute for Fusion Theory (JIFT), a bilateral program established in 1980, which coordinates fusion theory exchange activities between Japan and the United States.

A small anecdote illustrates one of the ways in which Wakatani played a key role in establishing the U.S.-Japan collaboration program in controlled thermonuclear fusion energy research. In 1980 a delegation of U.S. scientists accompanied by a Department of Energy representative (see Fig. 1) undertook a tour of major Japanese fusion facilities in order to explain the opportunities of the proposed new U.S.-Japan exchange program and build support for its approval. The first important visit on their tour was to the Heliotron Laboratory directed by Prof. K. Uo at Kyoto University. Here they were saved from failure by Wakatani's quick thinking. Professor Uo was then at the height of his career as the acknowledged "shogun" of stellarator/torsatron research in Japan. His Kyoto University laboratory was famous for successful Heliotron experiments that produced high-quality plasma confinement rivaling that of tokamaks, but without large internal currents. After the U.S. visitors had presented their vision for the proposed exchange program, it was clear that Prof. Uo was ready to say "No" (in the indirect Japanese manner). However, just before he uttered any irrevocable words, Prof. Wakatani understood what the true problem was and quickly said, "Uo-sensei, the exchanges would be with U.S. theorists and modelers, and I will keep them upstairs in my department." After a long silence Prof. Uo managed a pleasant face and said that such an exchange program could be started in the Heliotron Laboratory – but with the understanding that the visitors were to stay out of the experimental areas. One could say that due to Wakatani's perceptiveness, it became possible for the very successful JIFT exchange program to be launched. Soon thereafter, Prof. Russell Kulsrud from Princeton University spent a sabbatical at Kyoto University, working on electron thermal transport in helical systems. Subsequently a number of other U.S. scientists followed in his path to work in Kyoto with Wakatani and his theory group.

Wakatani served as a vital member of the JIFT Steering Committee for 13 years (Fig. 2) and, before that, a member of the Japanese Management Committee for JIFT for nine years). For two years (1998 and 1999), he also stepped in as the interim JIFT executive secretary on the Japanese side.

Besides his administrative role in JIFT, Wakatani was extremely active as an organizer of and participant in numerous workshops, both in Japan and in the U.S. Both of us worked closely and productively with him over the years in the arranging of JIFT activities and the organizing of workshops. In fact, Wakatani headed the delegation of Japanese scientists to the first JIFT workshop, held in 1980 at the newly created Institute for Fusion Studies at the University of Texas (Fig. 3). Table 1 lists all of the JIFT workshops for which Wakatani served as organizer. Rather impressively, in 1989 he co-organized four workshops, two at Kyoto University and two in the United States. In total, he organized 14 such workshops. One of these, to have been held in 1991, was, unfortunately, called off at the last moment; the JIFT Annual Report for that year quaintly noted that it had been cancelled "in view of the changing priorities in the U.S. fusion program." Besides the workshops that he organized, Wakatani also participated in many others, on a wide range of scientific topics (see, for example, Fig. 4).

We offer two further comments concerning Wakatani's valuable participation in the JIFT workshops. During the first decade of JIFT activities, Wakatani, in collaboration with Dr.

Fig. 1 Visiting U.S. delegation to promote JIFT in 1980, with Japanese hosts, in front of the Institute for Plasma Physics, Nagoya University. Front row (left to right): T. Kamimura, Y. Terashima, D. Baldwin, S. Hayakawa, D. Nelson, H. Kakihana, J. Dawson, T. Taniuti, W. Horton, M. Tanaka; back row (left to right): Y. Ohsawa, T. Hatori, Y.H. Ichikawa, I. Kawakami, K. Nishikawa, N. Yajima, T. Sato, M. Wakatani.

Fig. 2 Participants at the 1990 meeting of the JIFT Steering Committee (from the left): Y. Nishida, S. Stewart, M. Kono, M. Wakatani, W. Sadowski, J. Van Dam, T. Kamimura, D. Baldwin, W. Horton, and J. Dawson.

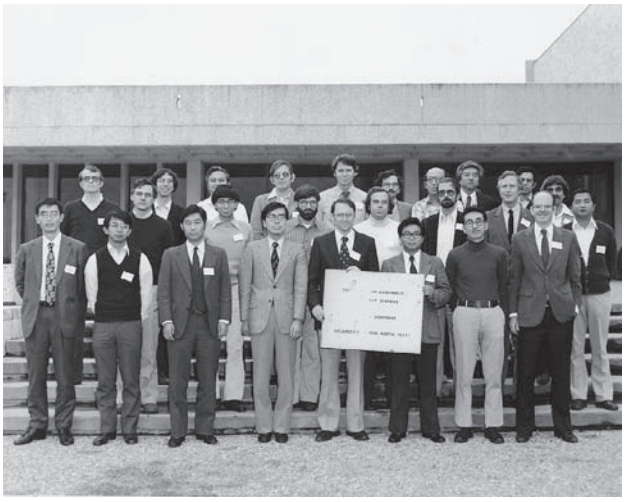

Fig. 3 Participants in the 1980 JIFT Workshop on Theory of Non-Axisymmetric Confinement Systems (University of Texas at Austin, 8-12 December). Front row (left to right): T. Watanabe, A. Fukuyama, J. Todoroki, M. Wakatani, D. Ross, T. Kamimura, H. Sanuki, W. Horton. Second row: R. Hazeltine, K. Shaing, M. Schmidt, A. Boozer, D. Spong, E. Maschke, C. Chu. Third row: J. Van Dam, R. Cohen, H. Berk, T. Cayton, G. Miller, A. Bayliss, D. Pearlstein, S. Yoshikawa, H. Strauss, T. Kaiser.

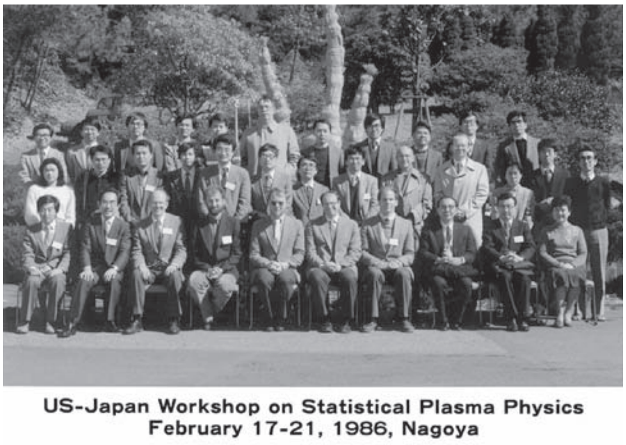

Fig. 4 Official photograph of participants at the 1986 JIFT Workshop on Statistical Plasma Physics. Wakatani is second from the right in the back row.

Table 1 List of U.S.-Japan Joint Institute for Fusion Theory workshops organized by Wakatani (title of workshop, names of co-organizers, date, and location).

Theory of Non-Axisymmetric Confinement Systems M. Wakatani, T. Kamimura, D. Ross December 8-12, 1980 — Austin	*Comparison of Theoretical and Experimental Transport in Toroidal Systems* M. Wakatani, B. Tang October 23-27, 1989 — Kyoto
Equilibrium, Stability, and Transport of Non-Axisymmetric Systems S. Yoshikawa, H. Weitzner, M. Wakatani December 14-18, 1981 — Nagoya	*Comparison and Benchmarking of 3D MHD Codes for Toroidal Applications* M. Wakatani, J. Todoroki, J. Johnson Planned for March 1991 — Nagoya Cancelled
Anomalous Transport Processes in Confined Plasmas M. Wakatani, R. Waltz February 4-8, 1985 — Kyoto	*Edge Turbulence, H-modes, and Shear Flow* M. Wakatani, P. Terry August 26-29, 1991 — Madison
Anomalous Transport M. Wakatani, R. Waltz February 23-27, 1987 — San Diego	*Eta-i and Resistive-g Turbulent* Transport M. Wakatani, W. Horton, A. Wootton (AIP Conference Proceedings 284) January 11-14, 1993 — Austin
Kinetic Effects, Second Stability and Alpha-Particle Dynamics in Toroidal Systems M. Wakatani, Y. Ichikawa, R. White January 9-13, 1989 — Princeton	*Transport Barrier in Turbulent Plasmas* W. Horton, M. Wakatani January 8-11, 1996 — Austin
Low-Dimensional Nonlinear Dynamics and Applications to Plasma Confinement T. Kamimura, T. Hatori, M. Wakatani, J. Cary, J. Finn, M. Lieberman July 24-28, 1989 — Colorado	*Plasma Turbulence and Transport in Toroidal Systems* M. Wakatani, B. Carreras October 29-31, 1996 — Kyoto
Theoretical Problems with Non-Axisymmetric Toroidal Configurations M. Wakatani, J. Johnson, G. Rewoldt October 16-20, 1989 — Kyoto	*Physics of High-Beta Systems* V. Chan, M. Wakatani September 6-12, 1999 — San Diego

Ben Carreras of Oak Ridge National Laboratory and others, went on to lead a series of U.S.-Japan workshops on MHD equilibrium and stability. At one point the JIFT Steering Committee requested a report that would summarize the broad range of research issues concerning macroscopic equilibrium and linear and nonlinear stability properties of magnetically confined plasmas in a variety of configurations. A small, invitation-only JIFT Workshop on 3D MHD Simulation, including 11 Japanese scientists (with Wakatani as one of the important participants), was held in March of 1986 for this purpose. The resulting report [18] described the major computational achievements to date and then laid out future directions for continued work. Our second comment is that Wakatani was very instrumental in leading a benchmarking study of helical system simulation codes. This constituted a long-standing JIFT effort – carried out collaboratively by Japanese, Russian, European, and U.S. scientists – to compare stability predictions from various different MHD numerical codes that had been applied to a common stellarator equilibrium configuration. Eventually this effort resulted in a major joint publication [19].

Finally, we note that in 1988 Wakatani had the honor of being chosen as the JIFT Visiting Professor to the U.S. He split his time between Oak Ridge National Laboratory and the University of Texas.

In addition to his extensive involvement in U.S.-Japan exchange activities, Wakatani was also an vigorous contributor to other international fusion collaborations. He played a leading role in the worldwide program to design the International Thermonuclear Experimental Reactor (ITER) device. In particular, he was the chair of the international Physics Expert Group on Confinement and Transport for ITER. As such, he contributed as one of the editors of the 500-page "ITER Physics Basis" document [20], published as a special issue of *Nuclear Fusion*. Subsequently and until his untimely death, he served as a member of the Topical Group on Transport and Internal Transport Barrier Physics, one of several such groups for the International Tokamak Physics Assessment (ITPA) effort.

5. Legacy of university leadership

Wakatani strongly contributed in terms of administrative leadership at Kyoto University, one of the premier institutions of higher education in Japan and worldwide. Here we mention two such areas.

He was a key member of the Kyoto University Council. As such, he assisted with a major re-organization within Kyoto University, which occurred in 1996. Also, he provided valuable direction in preparing for the re-organization of the entire national university system in Japan, to become effective in April 2004.

Second, he became Vice-Dean of the Graduate School of Energy Science at Kyoto University in April 2002. In this capacity he led a successive effort to establish a 21st Century Center of Excellence in Energy Science. In a national competition sponsored by the Japanese Ministry of Education, Culture, Sports, Science, and Technology, this center was funded for five years (2002-2006). Among our last correspondence with Prof. Wakatani were emails from him announcing this award and arranging exchange visits with the new center. He lived only three months longer. In a sense, this Center of Excellence is a capstone to his career.

6. Legacy of student guidance

As a professor at Kyoto University, Wakatani attracted and trained many outstanding students. Over the years we had the privilege of meeting many of his successive students. We watched them carry out their thesis research under his careful oversight and develop into mature and productive scientific leaders in their own right. Typically, a paper written by a Wakatani student was characterized by being well written, involving smart physics, focusing on a hot topic, and applying both skillful theoretical analysis and numerical simulations. Moreover, Wakatani was very willing to share credit with his junior colleagues. He usually put forward the student as the first author on a joint paper.

To his students he was always "Wakatani-sensei." Yet he had a human touch with them. In the autumn he and his students always went on a hiking expedition; at New Year's they would have a party together; whenever a student graduated, they held a send-off party [21]. Wakatani was the first to advocate an advanced graduate student as a participant in the JIFT exchange program; previously all the exchange scientists had been those already established in their careers. He also continued to keep an encouraging eye on his former students' progress after graduation.

The uniformly high quality of the students he produced is indeed impressive. In a review [22] written by Dr. John Johnson, a frequent collaborator of his, concerning Wakatani's last book, he made this comment: "I have always respected the author for the quality of students he produces... These students are a good demonstration of the usefulness of this book." Indeed, the Masters and Doctors theses of students who graduated under his tutelage comprised source materials for this excellent textbook.

We ourselves observed that in the 1990's, theory groups in Japan would even put in pre-requests to Wakatani for him to produce students who would have certain specific skill sets and for whom jobs would be already waiting.

Graduates of the "Wakatani school" now populate the various plasma theory groups in Japan. A list of the 17 graduate students whose Ph.D. thesis research he supervised is given in Table 2. By carrying on his methods and ideas, they constitute another vital part of his enduring legacy.

7. Legacy of family

It was very clear to us that Prof. Wakatani was a family man, proud of his charming wife (Yasuko, a piano teacher) and their three musically talented daughters (Seiko, Ayako, and Yohko). He especially enjoyed listening to his wife and daughters perform classical chamber music for piano and violin. Upon occasion he brought his family along with him

Table 2 List of Ph.D. students supervised by Wakatani.

NAKAMURA Yuji	ISHII Yasutomo	TATSUNO Tomoya
ICHIGUCHI Katsuji	MATSUMOTO Taro	FURUKAWA Masaru
WATANABE Kiyomasa	YOKOYAMA Masayuki	MIYATO Naoaki
YAGI Masatoshi	TAKAYAMA Arimichi	UNEMURA Takeshi
YANAGI Nagato	SHIRAI Hiroshi	SATO Masahiko
SUGAMA Hideo	IDOMURA Yasuhiro	

on visits to the U.S.

Dr. John Johnson of the Princeton Plasma Physics Laboratory and his wife, Barbara, told us that Wakatani once wanted his middle daughter to have an opportunity to practice her English. Consequently, when he went to Princeton for a weeklong workshop, he took her along. While he stayed at a hotel and attended the meeting, his daughter stayed with the Johnsons at their home. She was quite a help to them because at the time Mrs. Johnson had broken her arm. Dr. Johnson recalled that once when he tried to help wash dishes, the daughter shooed him out of the kitchen, saying, "A Japanese husband wouldn't do that!"

Wakatani understood that scientific progress often occurs through discussions carried out away from the pressure-filled atmosphere of conferences and workshops. He and his students often took visitors to see famous temples and other historical sights in Kyoto and Nara, while informally continuing to talk about scientific issues. In this way, making progress on a research problem with Wakatani was a wonderful experience.

He and his wife also extended many personal invitations to visit their home in Nara. In this respect, too, both of us are fondly grateful for their kind hospitality. Fortunately we had some opportunities to host Prof. Wakatani and his family here at Texas. He particularly enjoyed visiting the Alamo, a shrine to the battle for Texas independence in 1836 (which date he thought was comparatively recent, relative to Japanese history).

8. Legacy of personal character

In our opinion, a significant part of Wakatani's greatness was his outstanding personal character. As a scientist, collaborator, administrator, teacher, friend, and human being, he was a complete gentleman – courteous, dignified, calm, gracious, and considerate of others. He looked for praise-worthy characteristics in other people; he disliked being critical of others. When leading discussions he always gave all participants an opportunity to express their individual views. Even to those who opposed him, he was willing to listen, be fair, and provide helpful information.

His own presentations were thoughtful and reasoned, convincing his hearers on the basis of logical arguments and experimental evidence. He well understood that actions speak louder than words. We ourselves learned to listen carefully to every word he said, because he would proceed logically through his material – only once. One of us (WH) recalls one of Prof. Wakatani's talks, during which many of the scientists in the audience initially missed his key discovery of the onset of sheared flows in a collisional drift wave simulation, a phenomenon that is now invoked as the basis for transport barriers in many toroidal plasmas. In this respect perhaps it would have been helpful for Wakatani to be more emphatic or dramatic – but of course that would have been inconsistent with his reserved nature.

To work with Wakatani was both a privilege and a pleasure. It was, however, also a responsibility, because he expected much from his collaborators. He always attracted the brightest co-authors.

His personal integrity, in addition to his scientific creativity and leadership, were highly respected by the international scientific community. An indication of the international esteem in which he was held is the fact that he was selected to give the theory summary talk at the 1988 IAEA Fusion Energy Conference [23]. Wakatani was widely known to be modest, deep thinking, and reliable, with impeccable ethical standards. Interestingly, in his stellarator textbook, in the chapter that describes the reduced MHD equations for helical systems, he does not cite his own pioneering work, but instead, with characteristic modesty, gives a reference to the paper by Strauss [24] that generalized these equations to finite plasma pressure.

One of his former students told us that Wakatani-sensei had in his office a picture of Buddha with a peaceful face, and that Wakatani never got angry with his students, but was always very patient. Once, when a student was scolded by the laboratory director because the computer room was messy, Wakatani himself pitched in and helped the student clean it up.

Reviewing the list of papers he published, the books he wrote, the students he guided, and the international activities he was involved in, one realizes how incredibly diligent he was. Prof. Obiki in his obituary noted that at home, Wakatani often worked into the night after his family had gone to bed. Obiki also commented that instead of simply relying on his natural talents, Wakatani went on to make achievements that were obviously undergirded by layers upon layers of hard work.

His excessive obligations may have contributed to his early death. Very likely there were other important projects that he wanted to tackle. It certainly had been expected that he would continue to make great contributions toward Japanese and world progress in fusion energy.

9. Conclusion

Summed up, the achievements of Prof. Masahiro Wakatani can well be represented as a beautiful, towering mountain, like Mt. Fuji. The analogy is further appropriate since he stood at the summit of the fusion effort, his research was of zenith quality, and he was at the peak of his powers when he was unexpectedly taken from us.

Speaking for ourselves personally, but also on behalf of the entire worldwide community of fusion plasma physicists – we have lost a valuable scientific colleague and a close friend. Masahiro Wakatani is greatly missed. We will always honor his memory with deep respect and genuine affection.

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