Appendix A
E.J. Hopfinger. Experimental Study of Hetons

This Appendix is a summary of the experiments with hetons, conducted by Griffiths and Hopfinger [309, 310], aimed at illustrating heton generation in the laboratory. These experiments were motivated by the work of Hogg and Stommel [350, 351] who considered discrete, baroclinic geostrophic vortices that have the capacity of transporting heat. Real vortices have a finite core size and it was of interest to compare experiments with the theoretical, idealized point vortex solutions. Numerical solutions of, finite core size geostrophic vortices have followed and are presented in this book.

Griffiths and Hopfinger [309,310] considered the simplest situation of a rotating, two layer stratified fluid in a tank 100 cm in diameter and 45 cm deep with the fluid layers being of equal depth, H = 20 cm. The rotating tank was first filled with fresh water to 20 cm depth and then a sugar solution of desired density was slowly injected through a tube placed near the sidewall at the bottom of the tank. When the lower, denser layer reached 20 cm the system was left to spin-up to solid body rotation. It needs to be mentioned that the two layer system never reached complete solid body rotation. A weak azimuthal drift, generally $<3\%$ of the tank rotation, remained that switched from being axisymmetric to non-axisymmetric and reverse. Griffiths and Linden [312] interpreted this drift as being the result of a meridional Eddington-Sweet circulation, driven by the diffusion of solute across the isopycnals. The use of sugar solution instead of salt solution reduced this diffusion, hence the importance of this circulation. Lower diffusion resulted also in a thinner interface thickness, which was close to 2 cm at the time when the heton experiments were stared. The tank rotation was Ω = 1.0 rad s^{-1} $(f = 2s^{-1})$ and the reduced gravity $g' = g\Delta\rho/\rho$ was chosen such that the internal Rossby radius of deformation $\lambda' = (g'H)^{1/2}/f$ = 5, 10 and 15 cm. Note that the Rossby radius λ used in this book is defined as $\lambda = [g'h_1h_2/(h_1+h_2)]^{1/2}/f$, hence, when $h_1 = h_2 = H$, $\lambda = \lambda'/\sqrt{2}$.

The vortices in this two layer stratified, rotating system were generated by sources (anticyclones) and sinks (cyclones) placed at the free surface or the bottom. These vortices have a core radius R' of about 4 cm at which the azimuthal velocity is maximum. The vortex strength is a function of the flow rate. With sinks strong

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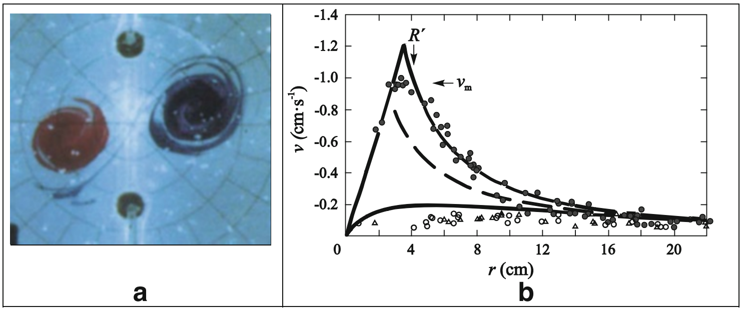

Fig. A.1 (**a**) Image of two anticyclones in the *top layer* taken at six tank rotation periods $(6T_\Omega)$ after vortex generation (after stop of the source flow). The source separation seen in (a) is 18 cm, $\lambda' = 14.1$ cm and $R' \approx 4$ cm. (**b**) Azimuthal velocity in a two-layer, $\lambda' = 7$ cm, anticyclonic vortex. •, upper layer vortex velocity at $9T_\Omega$ after vortex generation. *Open symbols* are for lower layer velocity. *Solid line* is solution of inviscid, quasi-geostrophic potential vorticity equations (see [310]). $R' \approx 4$ cm is intersection of theoretical solution with $v = v_m$. *Dashed line* is $v = s/2r$ of barotropic vortex of same strength

vorticity concentration can be achieved with the absolute value of angular velocity of the cyclonic vortices reaching $0.5 - 1.0\Omega$, whereas with a source (anticyclones) the angular velocity was limited to $0.3 - 0.5\Omega$. Note also, that, in order to prevent large perturbations, the source flow velocity needs to be kept low (large source flow area). A source or sink flow duration of 30 s (5 rotation periods) was sufficient to establish a well developed, depth independent vortex. During this time the vortex displacement remained negligible. The spin-down time of the vortices in the bottom layer (influence of bottom boundary) is $H/(fv)^{1/2} \approx 140$ s and is about twice as long in the top layer. The vortices were visualised by dye injection and the azimuthal velocity was measured by the streak line optical method. A typical image of two anticyclones generated in the top layer is shown in Fig. A.1a and the azimuthal velocity of a typical anticyclonic vortex is shown in Fig. A.1b.

In the Arctic oceans, a fresh source flow by ice melting can generate an anticyclone and ice freezing can give rise to a dense source flow, generating a cyclonic vortex in the top layer (see Fig. 1.2 in this book). In the laboratory it would also be possible to generate cyclonic vortices in the top layer by a dense source flow instead a sink flow. A tilted heton can emerge from baroclinic instability (Fig. 1.3 in this book).

It is of interest to compare experimental observations with numerical simulations presented in this book. The simplest case is a pair of vertical axis hetons corresponding to the situations shown in Figs. 3.46 and 3.47.

Figure A.2 illustrates an attracting heton pair in the laboratory tank. The anticyclones are generated in the top layer (red dye) by two sources at the free surface, visible in the images, and the cyclones are generated in the lower layer by two sinks at the bottom (blue and green dyes), placed at the same locations as the sources above; the vortices are initially of equal strength. The two (hot) hetons

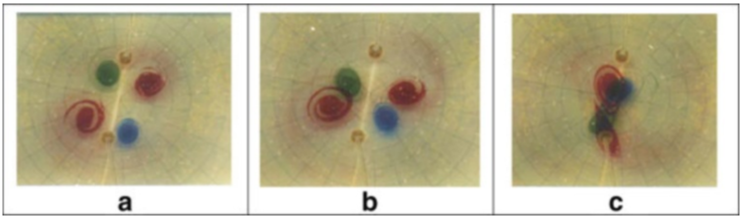

Fig. A.2 Photographs of an unstable, coalescing heton pair, initially separated by $2b^* = 20\,\mathrm{cm}$ (separation of injection tubes seen in the images). The suction tubes at the *bottom* are at the same location as the sources on *top* and initially the anticyclones (*red dye*) are of the same strength as to cyclones in the *bottom layer* (*green* and *blue dyes*). Initially, the hetons are axial but are torn apart by the vortex interaction in each layer. The vortex radii are $R' \approx 4\,\mathrm{cm}$, $\lambda' = 15\,\mathrm{cm}$ and images (a) to (c) are at 6, 15 and 22 T_Ω after vortex generation

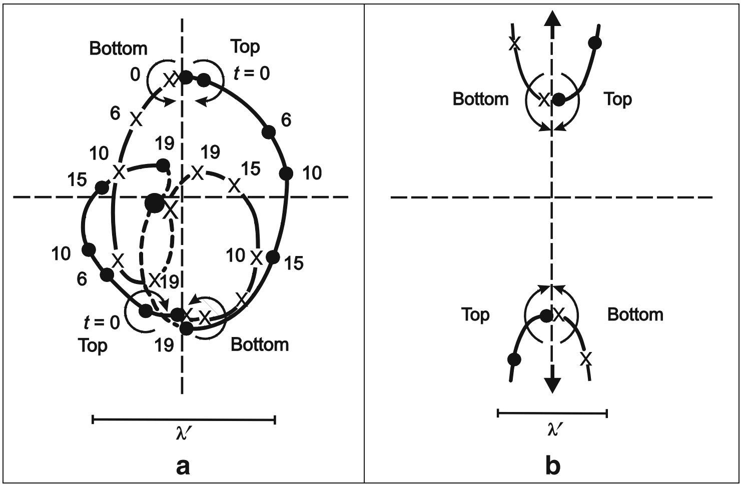

Fig. A.3 Paths of the centres of anticyclones in the *top layer* (*solid circles*) and cyclones in the *lower layer* (*crosses*). (**a**) Conditions corresponding to those of Fig. A.2. (**b**) initial heton separation $2b^* = 20\,\mathrm{cm}$ and $\lambda' = 10\,\mathrm{cm}$

generated in this way are initially separated by $2b^*/R' \approx 5$ and the dimensionless Rossby radius is $\lambda'/R' \approx 3.75$. In this case the interaction of vortices in the same layer override the interaction between vortices in different layers. The two anticyclones in the top layer orbit in the anticyclonic sense and the cyclones in the lower layer orbit in the cyclonic sense and eventually merge. The initially distance between the vortices in the same layer is $2b^* \approx 1.3\lambda'$, which is close to the critical value of $1.4\lambda'$ of point vortices Hogg and Stommel [350].

Figure A.3 shows the paths of the centres of the baroclinic vortices in the top and bottom layers, shown in Fig. A.2 ($2b^*/\lambda' = 1.3$), from the start, time $t = 0$ after generation to $t = 19T_\Omega$ and, finally, to complete merging (dashed traces). The paths of the vortices is not symmetric because of various imperfections inherent in experiments and because of asymmetric spin down. In Fig. A.3b the behaviour of the same heton pair is shown, but now for $2b^*/\lambda' = 2$. In this case the interaction between the top and bottom layer vortices is greater than the mutual influence of the vortices in the same layer. The hetons propagate in opposite directions. However, for this movement tilting is first necessary, which is caused by the interaction of the vortices in the same layer.

Griffiths and Hopfinger [310] determined the stability boundary for two anticyclones generated in the top layer. For barotropic vortices the critical distance is $2b^*/R = 3.3$; below this value vortices merge and remain stable, in orbital motion, above. Experiments showed that the stability boundary of baroclinic vortices depends strongly on the internal Rossby radius. For the conditions in Fig. A.3, that is $2b^*/R' \approx 5$, the stability boundary obtained by Griffiths and Hopfinger [310] is $\lambda'/R' \approx 2.4$. The heton repulsion shown in Fig. A.3b is close to this stability boundary, which, in the case of two hetons, likely to shift to somewhat larger values of λ'/R' because the vortex interaction in opposite layers opposes the interactions in the same layer. On the contrary, the conditions corresponding to Fig. A.3a are situated well within the merging domain $(2b^*/R' \approx 5, \lambda'/R' \approx 3.75)$.

The results presented in Figs. 3.39 and 3.40, are for $2b = 2b^*/D = 3$ and $\gamma = D/\lambda = 0.6$ and $2b = 3$, $\gamma = 0.7$ respectively. It is seen that the vortices coalesce (but never merge completely as in the experiments) in Fig. 3.39 and repel in Fig. 3.40. In the regime diagram $b - \gamma$ of Fig. 3.38, the coalescing heton pair lies in domain S_{3m} and heton repulsion (Fig. 3.40) in S_2. When taking $D = R'$, the corresponding positions in the regime diagram of Griffiths and Hopfinger [310] are at $\lambda'/R' = 2.35$ (coalescence) and $\lambda'/R' = 2.01$ (repulsion), in both cases the initial heton separation being $2b^*/R' = 3$. The value $\lambda'/R' = 2.01$ is close to the experimental stability boundary, which, as mentioned above, is likely to shift to slightly larger values in the case of hetons.

Now, comparing the experiments with the numerical results, the experimental conditions of the heton paths shown in Figs. A.3a, b are, respectively, $b \approx 2.5$, $\gamma \approx 0.37$ and $b \approx 2.5$, $\gamma \approx 0.56$. The latter lies well within the heton scatter domain S_2 whereas the former (heton merging) is close to the boundary of S_2 and S_{3m} but still in S_2. Discrepancies between experiments and numerical simulations are to be expected because the vortex radius is less well defined, the interface thickness is finite, the vorticity distribution in the vortex core varies and spin-down occurs.

Appendix B
M.A. Sokolovskiy. In Memory of My Teacher

Vadim Fedorovich Kozlov
(1933–2005)

Vadim Fedorovich Kozlov was born on March 17, 1933 in Vladivostok into a family of seamen. His father, Fedor Kirillovich Kozlov, was a sea captain; his mother, Valentina Iosifovna, née Gein, was a seaman's wife and kept the house. In her youth, she also studied in a marine technical school, but after the birth of her son, took charge of his upbringing. Later, she also contributed much to the upbringing of her grandson Kirill. These were marine families. His paternel elder brother, Matvey Kirillovich Kozlov, was also a sea captain, and the younger brother, Ivan Kirillovich Kozlov, was a chief engineer of Sakhalin Shipping Company. The maternal grandfather, Iosif Antonovich Gein, worked as a chief engineer on ships in the Far East and Black Sea Shipping Companies since the 1910s. The uncle, Anatoliy Iosifovich Gein, also worked as a chief engineer on ships of Murmansk Shipping Company, while another uncle, Gleb Iosifovich Gein, served in the navy.

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Vadim Fedorovich spent his early childhood and schooldays in his hometown. After graduating from school with a Silver Medal, VF enrolled without examination (according to the rules of that time, the persons who had graduated from school with a Silver Medal could be enrolled after an interview) in the Division of Mechanics, the Faculty of Mechanics and Mathematics, Moscow M.V. Lomonosov State University (MSU).

In that time, the faculty was situated in its historic building in Mokhovaya Street, but in 1953 it moved into the new high-rise building in Leninskie Gory. The students, including VF, settle in a comfortable dormitory in MSU Main Building. After their second year, students were to choose a department for their area of expertise. VF chose the Department of Gas and Wave Dynamics, which was then headed by Academician of Uzbek Academy of Sciences, Kh.A. Rakhmatulin. After graduating from the University, VF was invited to continue his study as a postgraduate student.

A curious thing that happened with VF during his postgraduate study taught him a valuable lesson: to keep up with the scientific literature. It was like this: the research adviser formulated a problem for him about the reflection of an acoustic wave from a deformable plane. The young postgraduate student solved the problem and reported the obtained result at a conference. Next, he wrote a paper, which he was going to publish in the Vestnik (Herald) of Moscow State University. The reviewer of his paper was firm but fair: he informed the author that this result was obtained by Rayleigh as long ago as 1878. Reviewing the past many years later, VF joked: “Lord Rayleigh and I have obtained an elegant solution”, and continued: “Though I did these 80 years later, but still independently!” This lesson was as severe as useful. As a result, the future professor finished his post-graduate studies without defending his thesis. (Scientists in Russia have two scientific degrees, i.e., Candidate of Science and Doctor of Science; the successful completion of post-graduate study is commonly a defended Candidate thesis).

Immediately after his graduation from the university, VF married his classmate Tatyana Leonidovna Gavrilova. She, also graduated from the Faculty of Mechanics and Mathematics, was doing her postgraduate studies in the Department of Applied Mathematics, Steklov Mathematical Institute, Russian Academy of Sciences, under scientific supervision of A.A. Lyapunov.

After the completion of their postgraduate studies in 1960, the newly married couple completed the Moscow period of their life and moved to Vladivostok. In Vladivostok, they immediately started their teaching activity in the Far Eastern State University (FESU). VF started learning the fundamentals of lectureship at the Faculty of Physics and Mathematics, where he lectured on the basic courses of *Theoretical Mechanics* (for students in mathematics) and *Methods of Mathematical Physics* (for students in physics) and carried out practical exercises in those courses; he also was a scientific supervisor of term and (later) graduation works in both lines.

In 1964, after the organization of the Faculty of Geophysics in FESU, he transferred to the Department of Oceanography of this Faculty, where he lectured on basic and special courses, such as *Higher Mathematics*, *Hydromechanics*, *Dynamics of Currents*, *Nonlinear Problems of Current Dynamics*, *Theory of Geostrophic Flows*, *Theory of Gravitational Waves*, *Nonstationary Acoustic Waves*. He also led seminars on wave dynamics and dynamics of flows.

It will be observed that VF was a masterly lecturer. His direct or indirect disciples will always remember his splendid lectures. Although the theory of oceanic flows was absolutely new for VF, he, due to his extraordinary capacity for work and the ability to see the essence of problems, very quickly learned the basic works in this field and prepared a course of lectures, forming the basis for teaching this discipline. Several years later, he published an excellent textbook [449], in which he generalized all results of the theory of stationary flows in the ocean available by that time. All books went like hot cakes. Not only students and postgraduates, but also many experts in oceanography appreciated the basic character of this work and the exhaustive list of references in the field. Until his last years, VF received requests from his colleagues to send them the book, but, even in his private library, he had only one copy of it. The former disciples of VF, who became professors in universities, used this book as a basis for their lectures to the following generations of students in oceanography. Large teaching activity in the first years of his work in the university was not an obstacle for VF in his research. From the first days he joined the researches in Marine Physics.

In the early 1960s, a weekly seminar on Marine Physics started working at the Department. For two decades, this seminar was essentially the center of oceanographic studies in Vladivostok. This seminar was attended, in addition to members of the Department, by professors and researchers from other educational and research institutions. VF was a permanent member of this seminar, and he set there a high level of reports and discussions. Even his first publications on the parameterization of vertical turbulent exchange in the ocean and studies of the specific features of subequatorial circulation placed him among the leading theoretical oceanographers in the country.

These studies, supplemented by results in the theory of thermocline, formed the basis for his candidate thesis. He prepared the thesis himself, without a scientific advisor, and, according to the existing requirements, he needed in a special permission of the State Commission for Academic Degrees and Titles to defend it. The Commission gave its approval as an exception, provided the defense should take place with two doctors of science as official opponents (generally, one of the opponents is a candidate of science). The official opponents were the well-known oceanographers A.I. Fel'zenbaum and A.S. Sarkisyan, who appreciated the merits of VF very high.

Soon after the defense of his thesis, VF transferred into the Pacific Oceanological Institute, Far East Branch, USSR Academy of Sciences (POI FEB RAS), as a senior researcher in the Laboratory of Thermal Processes and Marine Dynamics. From 1970 to 1974, VF was working at this institute, keeping close contacts with the university, where he lectured several courses and supervised the graduation works of students from the Departments of Oceanography and Computational Mathematics.

The main scientific interests of those years are represented by works aimed to develop mathematically grounded diagnostic calculations of oceanic flows and a concept of integral quasi-geostrophic models reflecting the important properties of three-dimensional models. The paper [450] on the mutual adaptation of the mass and current fields to the bottom topography, in my opinion, is among the brilliant works of VF. The classes of partial analytical solutions of simplified nonlinear equations of ocean dynamics are still most complete. He suggested in this work carrying out a detailed typification of the World Ocean areas by analyzing the contribution of individual terms of the considered equations. Unfortunately, the evaluation of these contributions based on real oceanographic data was never implemented. No doubt, this is an omission of practical oceanographers.

In 1974, the primary employment of VF again became FESU, though now it was the Department of Computational Mathematics, Faculty of Mathematics. At this department, VF prepared an ingenious author's course *Computing Techniques* for students specializing in *Applied Mathematics* and introduced a new area of expertise *Application of Numerical Methods in Oceanography*. He delivered lectures on several special courses for students in this field: *Perturbation Methods in Applied Mathematics*, *Numerical Solution of Problems in Ocean Dynamics*, *Methods for Fluid Oscillations Calculation*, etc. During the 5 years of his work with this department, he "set on their feet" many skilled experts in the application of numerical methods and computation engineering.

Following the principle: “the researcher should change something in his interest every five years”, VF again accepted an invitation to transfer to POI FEB RAS. This decision was partially due to the appearance in POI of Valeriy Isaakovich Klyatskin, who transferred from Moscow to Vladivostok for permanent work. VF very much disliked any administrative activity, so he readily agreed to take a position of senior researcher in the Laboratory of Wave Processes, created by V.I. Klyatskin. Later on, when, during POI restructuring, the Laboratory of Wave Processes became a division with the same name, VF had to agree to lead the Laboratory of Geophysical Hydrodynamics created in the division and consisting of his disciples.

A unique feature of VF as a scientist is that, since his graduation from MSU, he never belonged to any school and formulated himself all the problems for his research work. No doubt, he can be regarded as a founder of the Far Eastern Russian School of Geophysical Hydrodynamics. Nowadays, this school is supported by K.V. Koshel and S.V. Prants.

In the 1970s, VF focused on the problem of the effect of bottom topography on oceanic flows. He solved several difficult and elegant problems of vortex structures’ generation by irregularities of the bottom relief and shoreline, including stationary Taylor vortices and leeward Rossby waves [451–454, 481, 483, in particular]. A generalization of these basic results is given in book [456] and in his Doctorate thesis defended in 1984.

Having the “doctoral standing” in fact, VF for a long time avoided starting a routine work of preparing a thesis. As in the case with the position of the Head of Laboratory, he again was compelled to yield to the “situation”: in the course of a cognac-drinking session during the 2nd All-USSR Oceanological Congress (Yalta, 1982), A.S. Sarkisyan and V.I. Klyatskin, succeeded in making VF to give a word of honor to put hand to this task. The thesis was written within 3 months and, after the completion of appropriate procedures, brilliantly defended at the Scientific Council of the Marine Hydrophysical Institute in Sevastopol.

The history of science knows many real-world examples when an interesting idea comes to the minds of several people practically at the same time. VF knew quite well that the 2D movement of fluid particles in a continuous motionless depends only on the boundary configuration of areas with nonzero relative vorticity. He developed a numerical algorithm for calculating flows under such formulation. It was only to charge a student or a postgraduate with writing a computer program and to solve a simple model problem. Several young persons tried to do that but all failed. However, in 1979, the American mathematicians Zabusky, Hughes and Roberts published their famous work on contour dynamics for two-dimensional Euler equations [1006], and implemented the same idea. VF proposed his disciple and then colleague, V.G. Makarov, to put aside his work and to put hand to this problem. Viacheslav wrote the required software package. This software was more efficient and user friendly than the American one (moreover, it enabled a very wide class of generalizations), but, there is nothing to be done, the Zabusky group merited to be pioneers in the creation of the Contour Dynamics Method (CDM).

In 1983, VF published his first work on CDM [455], which was focused on the application of this method to the problems of geophysical hydrodynamics. Two years later, VF gave the first generalization of the method to the case of a continuously stratified medium [457]. In those years, almost all researchers from Vadim Fedorovich's laboratory joined the work aimed to solve numerous problems with the use of this approach [334, 458, 462, 464, 465, 472, 473, 477–480, 484, in particular, and many other papers written after the death of VF]. Anyway, the more than 10-year period of work, associated with the application of CDM and its modifications [459–461] for numerous problems, was extremely fruitful for both VF and his colleagues.

Works [458] and [459–461] are worth special mentioning. In the first paper, VF suggested a general algorithm for constructing asymptotic expansions, what allowed determining of the boundaries of vortex patches for stationary states of translational and rotational types of various vortex structures up to the fourth degree of a small parameter. This paper specifies appropriate expansions for already known states, gives some new solutions, and describes an exhaustive procedure for their construction. The second series of papers gives an expansion of the well-known problem of elliptic Kirchhoff vortex to the case with the involvement effect taken into account. Both papers are examples of qualitatively new generalizations of classical results.

In the next 5 years of his scientific life, VF was interested in the problem of construction of background flows. The concept, he formulated in [463], was developed up to its implementation both for model cases [466], and for natural water bodies (the seas of Okhotsk and Japan) [474–476].[1] The background flows determine the base state of horizontally uniform and steady-state distribution of potential vorticity, which provides a global minimum of mechanical energy for some

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[1] Currently, research in this direction is developed by V.V. Novotryasov and D.V. Stepanov in POI FEB RAS.

area with given geometry of its boundary and bottom topography. The possible mass exchange at the boundary is taken into account. Thus, the specified background state of the system allows one to uniquely determine a flow field that is dynamically consistent with the field of relative or potential vorticity.

This concept turned out to be surprisingly fruitful in studies of many phenomena taking place in the ocean and associated with chaotic mixing of fluid particles, e.g., the diffusion of a conservative admixture. The interest VF showed to chaotic dynamics was due to his desire to understand the nature of diffusion of vortex filaments, separating from vortices and clearly traceable in CDM-based calculations. These filaments form every time when an initially compact vortex moves either in a shear flow, or it decays because of its own instability, or, finally, when two (or more) vortices with the same sign are close enough to one another. Problems of chaotic dynamics of flows in different areas [380–382, 467, 468, 470, 471] were the last object of VF's scientific interest.

For publication, VF preferred the journal "Izvestiya, Atmosphere and Ocean Physics"; 37 his papers got out there. The sympathy was mutual: the editorial board of the journal published their tributes on the occasions of VF's 60th and 70th anniversaries.

Since 1997 until his last days, VF in cooperation with S.V. Prants guided a permanent seminar on nonlinear dynamics in POI. As in the case with oceanographic seminars in FESU, researchers from many allied institutions gathered at its meetings, and they still do this. At this seminar, all the results obtained by VF in the field of chaotic dynamics were also discussed.

VF's devotion to books should also be mentioned. Since his studentship, he started forming his scientific library. Later, because of the evident lack of place in the bookshelves in his home library, VF introduced a rule, according to which his bookshelves were to contain no more than 2,000 the most necessary books. Other books (after thorough choice) would be transferred to his office in the institute. The library of POI still contains a splendid Vadim Fedorovich's contribution, including copies of papers and books on different fields of oceanology. He paid special attention to journal publications In abstract journals and, recently, in the Internet he traced new studies in the fields of interest for him.

During the years of his active work, VF collected several tens of thousands of preprints and copies of papers. Many colleagues addressed him with bibliographic questions and immediately received the required paper from the bowels of his famous bookcases. His collection is unique. Now it is in full disposal of the personnel of Geophysical Hydrodynamic Laboratory, where VF was working until his last days.

VF lived in the central part of Vladivostok and took suburban electric train to reach the institute, situated in the city's suburbs. On his way to the institute, he looked through new journals and preprints of papers delivered by mail. One day in the mid-1980, when we were working on the problem of stability of two-layer vortex, he entered the Laboratory and asked me whether I knew the word "heton". I confessed that this was the first time I heard this word. With a mischievous glint in his eyes, he took from his briefcase a preprint of the new paper by Hogg and Stommel [350], in which this term was introduced. Since then, the "heton" has become an important component of my life, a fact of which this book is a confirmation.

On January 9, 2005, Vadim Fedorovich departed from this life, what decreased the amount of intellect in the world. One can hardly say how many new and fruitful ideas could have been generated by the inquisitive mind of our Teacher, but, unfortunately, the fate gave him too short term. VF was an open man; he always shared his knowledge and experience with all who needed in them.

I was lucky to have had a privilege of practically daily converse with VF during the 20 years of my work in Vladivostok. In one of our numerous informal conversations, I mentioned some of his works that, in my opinion, were of greatest interest (see above) and asked him whether he agreed with my estimate. VF approved my choice and, with his intrinsic sense of humor, he added: "It is brief, but quite sufficient for my epitaph!" All who knew him will remember this wise, life-loving, and witty person.

Acknowledgements I am sincerely grateful to Tatyana Leonidovna Gavrilova for information about Vadim Fedorovich's relatives.

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