The Prehistory of the Belousov-Zhabotinsky Oscillator

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It would not take long to assemble an imposing catalogue of examples illustrating the resistance of human nature to observations that do not fit into existing theory. Discoveries which eventually force on textbooks a change of perspective and emphasis are therefore commonly associated with the names of a second generation of investigators, the originator having finished his contributions before the spotlight turned in that direction. But it is unusual for the first meticulous investigation actually to remain unpublished for 30 years before being exhumed for national and international recognition. The 1980 award of the Lenin Prize to B. P. Belousov, A. M. Zhabotinsky, V. I. Krinsky, and G. R. Ivanitsky celebrated such a discovery.

The explosively growing literature of chemical oscillators can be traced back to several independent starting points, the most recent and influential of which is Zhabotinsky's original analysis (*1*) of the mechanism of Belousov's citric acid/bromate/cerium reaction (*2*). Belousov's single publication on the subject (*2*) contains the recipe but only sketchy conjectures about the mechanism, with no demonstration of rhythmic activity. It appears without citations on two small pages just before a paper by Belousov and his colleague A. P. Safronov on quite a different subject in the proceedings (in Russian) of a symposium on radiation medicine. This abstract was cited only once outside Russia before the 1970's (*3*). Of those authors who have cited the abstract, probably few have actually seen it. I was among the first to publish on this subject in the West, but it was not until 1975 that I received from Endre Kőrös in Budapest a translation of the Belousov paper, nor until 1978 a xerographic copy of the original in Russian (*2*) from Zhabotinsky.

On a recent visit to the research city of Puschino, south of Moscow, I had an opportunity to learn more of the history of this remarkable reaction, largely by conversation with Zhabotinsky (Fig. 1). With a quiet smile, perhaps surprised by my ignorance, Zhabotinsky told me much that seems common knowledge in Russia about the origins of the cerium/bromate oscillator, but has never before appeared in English. Several Russian publications (*4–6*), a movie (*7*), and Zhabotinsky's historical review (*8*) have been of help in reconstructing the story.

The story begins around 1950 with the work of B.P. Belousov (Figs. 2 and 3), then already 57 years old and head of a Laboratory of Biophysics of the USSR Ministry of Health. Belousov had studied chemistry in Zurich before the October 1917 Revolution, and was professor of chemistry in the USSR before World War II. His interests included biochemistry, and 1950 found him endeavoring to model catalysis in the Krebs cycle using the metal ion cerium instead of the protein-bound metal ions common in the enzymes of living cells. The Krebs cycle is a universal part of metabolism by which acetyl residues are oxidized to carbon dioxide in mitochondria. It is called a "cycle" not because it oscillates in time, but just because the reaction sequence leads in a circle, much as in any geochemical cycle. Much to Belousov's surprise, his test-tube caricature, a solution of citric acid in water with acidified bromate as oxidant and yellow ceric ions as catalyst, turned colorless and returned to yellow periodically for as long as an hour (at room temperature) while effervescing carbon dioxide!

Belousov undertook serious study of this peculiarity,

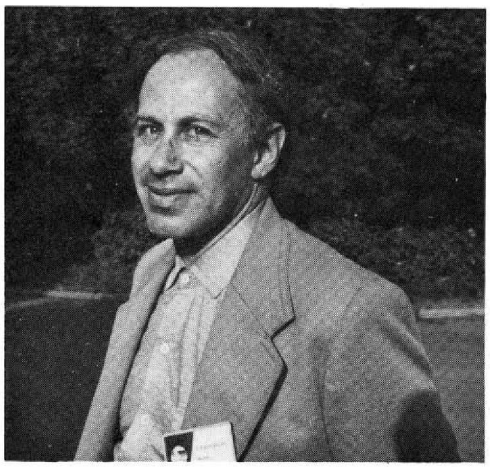

Figure 1. Anatol M. Zhabotinsky, July 1983, at the end of a walk with the author in Puschino, USSR.

measuring, for example, the effects of temperature and acidity on the oscillator's period (*6*). He notes that the oscillator quits when either the oxidant (bromate) or the organic substrate (citrate) is depleted, and it resumes when the missing ingredient is restored. He presents a tentative scheme for the reaction mechanism. He thanks Safronov for perfecting the given recipe and for suggesting iron phenanthroline (ferroin) as a superior color indicator/catalyst. He includes sequential photographs alongside a stopwatch, and even oscillograph traces showing details of the timecourse at high resolution. He reports construction of a vertical gradient of local oscillator period in a graduated cylinder, and its self-organization into horizontal strata of alternating color. Readers of the modern literature on oscillating reactions will recognize here anticipations of a dozen excellent research papers from laboratories in Germany (*9*), Belgium (*10*), Hungary (*11*), the United States (*12*), and France (*13*) up to about 1973. Even the motivation of the original discovery was eventually reconstructed by noticing that many successful substitutions for citric acid happened to be components of the Krebs cycle or close analogs (*14*). None of these investigations drew on Belousov's work, for the excellent reason that it was never published (apart from the obscure symposium abstract of 1959)!

The referees rejected Belousov's 1951 manuscript, and with it much that was excitedly rediscovered outside the Soviet Union during the next two decades. The editor of Belousov's chosen journal advised him (apparently without testing the simpler recipe) that his "supposedly discovered discovery" was quite impossible, and would merit publication only if accompanied by a demonstration that existing theory was flawed. Belousov's choice was to go back to the laboratory and decipher the mechanism with still more care. Submitting his comprehensive analysis six years later as a new and enlarged manuscript to another chemical journal, he faced hardened skepticism. The editor recommended abbreviated publication only as a claim, truncated to the length of a letter to the editor, deleting the newly furnished, convincing evidence. Infuriated,

Figure 2. Boris Pavlovitch Belousov at study prior to his discovery of the oscillating reaction (1930–35), courtesy of A. V. Panfilov and S. E. Schnoll.

Belousov, then 64 years old, resolved never to publish at all, and withdrew. But he preserved the original manuscripts (*4*, *6*).

Meanwhile his recipe circulated among the faculties of Biophysics and Physics at Moscow State University and of the Biophysics Institute of the USSR Academy of Sciences in Puschino. But it seems no one knew the recipe's origin. After a laborious search, Belousov was found and prevailed upon to write the obscure 1959 abstract (*2*). Even Zhabotinsky was unaware of it for years. At the end of 1961, as a graduate student of biochemistry at Moscow State University, Zhabotinsky had been assigned by S. E. Schnoll to experiment with a citric acid recipe of unknown origin. His vigorous investigation marked the real beginning of interest in this reaction. In the spring of 1962 he discussed his findings with Schnoll and sent draft of a manuscript to Belousov. Belousov replied with a kind letter expressing his satisfaction with the development of his original work, enclosing an unpublished manuscript and citation (*2*), which Zhabotinsky then located in the library and added to his list of citations. Though he kept Belousov advised of progress by mail, Zhabotinsky's several attempts to arrange a personal meeting were politely declined with diverse excuses. They never met.

At least ten papers had been published in Russian about this oscillating reaction before the first in English (*3*, *15*). Others were provoked by the summer 1968 Symposium on Biological and Biochemical Oscillators in Prague (*16*), attended by Zhabotinsky and colleagues, but not Belousov. The name "Zhabotinsky reaction" became common in the Western literature, changing to "Belousov-Zhabotinsky" only in recent years. But no one outside Russia had any idea of the full story before Zhabotinsky sent me the 1981 Gorky proceedings, nor until I translated parts (*5*) in 1983. In the proceedings it is told that Belousov had died 12 June 1970, too early to enjoy recognition of his principal discovery, but highly regarded by his colleagues not only for his ability as a scientist but also for personal traits much valued in his work as department head. His rejected work is also reprinted in the proceedings (*6*), though it had already been resurrected piecemeal in the discoveries of a dozen younger scientists who might never have heard his name at the time. Testimonials to the importance of his discovery were solicited from scientists inside and outside the Soviet Union in 1979. In 1980 Belousov was awarded the Lenin Prize, together with A. M. Zhabotinsky, V. I. Krinsky, and G. R. Ivanitsky. His work and theirs are celebrated in two award-winning movies (*7*, *17*) soon to become available in the West. The seed that Belousov planted has since arborized and ramified enormously. Fruits are collected in a comprehensive bibliography, together with recent review papers and a translation of the manuscript dated 1951 in a forthcoming book edited by Field and Burger (*18*).

Acknowledgment

I thank A. M. Zhabotinsky for the privilege of editing his first English manuscripts in 1968 and for encouragement in investigations since, V. I. Krinsky and the Akademia Nauk CCCP for invitation to Puschino in summer 1983, the U.S. National Science Foundation and Purdue Research Foundation for travel funds, and A. V. Panfilov and S. E. Schnoll for portraits of Belousov.

Note Added in Proof

The 4th issue of *Novoi Mir* in 1984 reportedly carries an article (in Russian) by Polishuk about Belousov.

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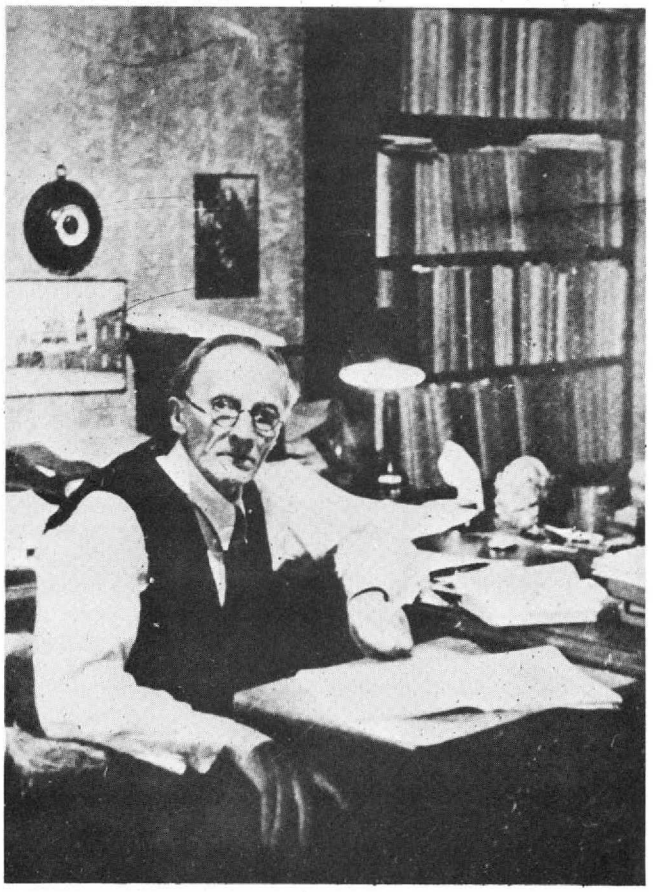

Figure 3. Boris Pavlovich Belousov at his desk in later years (1956–58), courtesy of A. V. Panfilov and S. E. Schnoll.

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