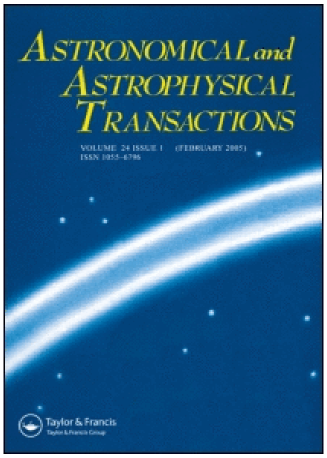

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

I.S. Shklovsky and modern radio astronomy

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Online Publication Date: 01 October 2006
To cite this Article: Rudnitskij, G. M. (2006) 'I.S. Shklovsky and modern radio astronomy', Astronomical & Astrophysical Transactions, 25:5, 363 - 368
To link to this article: DOI: 10.1080/10556790601165700
URL: http://dx.doi.org/10.1080/10556790601165700

Astronomical and Astrophysical Transactions
Vol. 25, Nos. 5–6, October–December 2006, 363–368

I.S. Shklovsky and modern radio astronomy

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(Received 2006)

Iosif Samuilovich Shklovsky is one of the founders of radio astronomy as a leading branch in the modern science. Under his leadership in 1953 the Radio Astronomy Department was formed at the Sternberg Astronomical Institute of Moscow State University. Shklovsky's research covered a large variety of topics in radio astronomy, space research, solar physics, X-ray astronomy, etc. In this contribution, Shklovsky's life story is reviewed, including the famous expedition to Brazil for radio observations of the solar eclipse. His main works are presented, such as the prediction of the possibility of observing the 21 cm radio line of neutral hydrogen in the interstellar medium together with some molecular radio lines, the explanation of the spectrum of the Crab Nebula in the optical and radio ranges by a unified synchrotron mechanism, and his studies on the radio emission of the solar corona, including the explanation of drifting solar radio bursts by a plasma mechanism. Other research achievements are reviewed, among which are his idea on the artificial comet implemented during the first lunar launches, and his work on the problem of the search for extraterrestrial intelligence.

Keywords: History of astronomy; Radio astronomy; I.S. Shklovsky

1. Brief biography

Iosif Samuilovich Shklovsky (figure 1) was born on 1 July 1916 in a small town of Glukhov, now in Ukraine. In 1931, Shklovsky graduated from a 7 year school in Akmolinsk (now in Kazakhstan) and then worked for 2 years in railway building. In 1933, he became a student at the Physics and Mathematics Faculty of the Far East University in Vladivostok. From 1935, he studied at the Physics Faculty of Moscow State University. In 1938, Shklovsky graduated from the Optics Department and became a post-graduate student at the Sternberg Astronomical Institute of Moscow State University. Since then, all his research activity has been associated with this Institute. His supervisor was the famous Russian astronomer Nicolai N. Pariiskii, who taught the fundamentals of astronomical science to the young post-graduate physicist. Shklovsky always recalled with gratitude his first teacher in astronomy.

When in 1941 the war began, Shklovsky was not drafted to the army because of his weak eyesight. Together with the University, he was evacuated to Central Asia and then to Sverdlovsk, where he continued his research and teaching. In 1943, Shklovsky returned to Moscow and, in 1944, he presented his candidate thesis (PhD equivalent) entitled 'The electron temperature

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Astronomical and Astrophysical Transactions
ISSN 1055-6796 print/ISSN 1476-3540 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10556790601165700

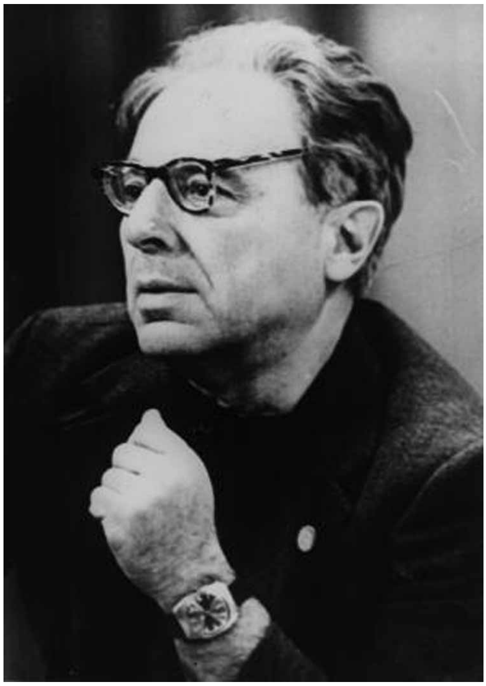

Figure 1. Iosif Samuilovich Shklovsky.

in astrophysics'. The idea itself was novel at that time, to describe the motion of electrons separately by the term 'temperature', and Shklovsky was one of the first scientists to use in the Russian-language literature the word 'plasma'.

In 1947, Shklovsky took part in the Soviet expedition to Brazil to observe the total solar eclipse. He always recalled this expedition as one of the brightest events in his life. The programme of this expedition on the ship *Alexander Griboedov* included optical and radio observations of the eclipse of 20 May 1947. The observations at a wavelength of 1.5 m from the ship demonstrated for the first time that the radio source associated with the Sun was extended and that the signal did not disappear even at the moment of total eclipse. This suggested that the origin of solar radio emission is the solar corona. Shklovsky did not take part in the radio experiment; he was a member of the optical team, which moved inland to perform their observations. Unfortunately, the weather was bad, and this programme failed. However, Shklovsky was deeply impressed by the results of the radio experiment, and this determined the direction of his science career for many years.

In 1953, Shklovsky founded the Department of Radio Astronomy at the Sternberg Astronomical Institute and remained the Head of this Department until the end of his life. In 1969, he also founded the Department of Astrophysics in the new Space Research Institute of the USSR Academy of Sciences.

Shklovsky received many awards for his outstanding science work. He was awarded the Lenin Prize of the USSR in 1960, the Karl Jansky Prize from the National Radio Astronomy Observatory of the USA in 1968 and the Bruce Medal from the Astronomical Society of the Pacific in 1972. Shklovsky was elected a Corresponding Member of the USSR Academy of Sciences, a Member of the National Academy of Sciences of the USA, a Member of the Royal Astronomical Society of London as well as a member of other academies and societies.

Iosif Samuilovich Shklovsky died on 3 March 1985 in Moscow.

2. Solar physics

As stated above, solar physics was one of the first directions of Shklovsky's research. Since the 1940s he advocated the idea of the hot corona ($T \approx 2 \times 10^6$ K), which was not widely accepted at that time and severely criticized. In his monographs [1, 2], Shklovsky presented his views and gave explanations of many observed phenomena; in particular, he identified some emission features in the coronal spectrum with the lines of highly ionized iron, nickel and other atoms. Shklovsky showed that the solar radio emission consists of two components: thermal free–free emission of the hot corona and sporadic bursts produced by solar active regions. He interpreted the observed drifting radio bursts of the solar radio emission by the mechanism of plasma oscillations excited by a beam of relativistic electrons that are accelerated in a solar flare. Shklovsky's prediction was also that the hot corona would emit in the ultraviolet and X-ray regions, which was confirmed by subsequent space-borne experiments.

3. Spectral radio astronomy

In 1949, Shklovsky addressed the possibility of observing spectral lines in the radio wavelength range. His interest was stimulated by the paper of the Dutch astronomer van de Hulst about eventual radio emission in the hydrogen line at $\lambda = 21$ cm. In [3], Shklovsky calculated the probability of this magnetodipole transition between the hyperfine structure levels of the hydrogen atom. This probability turned out to be quite low, $A = 2.85 \times 10^{-15}\,\mathrm{s}^{-1}$. Nevertheless, Shklovsky found that the 21 cm line should be observable from interstellar gas clouds. Indeed, this line was successfully detected 2 years later, almost simultaneously in the USA, The Netherlands and Australia. This line has become a powerful tool for studying interstellar gas in our Galaxy as well as in other galaxies. Another line of the hydrogen isotope ^{2}H (deuterium) at $\lambda = 91.6$ cm, also considered by Shklovsky, has not yet been reliably detected.

In the same paper [3], Shklovsky also calculated the frequencies and probabilities for some transitions in simple diatomic molecules (OH, CH and SiH), the so-called Λ-doubling transitions. For the hydroxyl radical OH, there are four electrodipole transitions at $\lambda = 18$ cm. In 1963, these lines were detected in interstellar gas in absorption from the non-thermal radio source Cassiopeia A. Then 2 years later an unexpected discovery followed, when the 18 cm lines were found in emission towards some galactic radio continuum sources, and this emission was quite unusual. The 18 cm lines were intense, very narrow and often 100% circularly polarized. This gave grounds for doubts about the proper identification of the lines with OH transitions. The unknown substance radiating such lines was nicknamed 'mysterium'. However, it was soon understood that the observed emission still belonged to OH radicals but that it was excited in a quite specific manner. Under the action of some mechanism, OH molecules are pumped to the upper levels of the 18 cm transitions and can amplify manifold the background radio continuum at the line frequencies by stimulated radiation; this is the maser effect known for laboratory quantum generators of microwaves ('maser') or light ('laser'). Thus it was found that the maser mechanism can operate in cosmic sources too. In his paper of 1969 [4], Shklovsky gave a detailed interpretation of the observed OH masers as sources in the vicinity of young stellar objects, including the 100% circular polarization, which he attributed to the Zeeman effect in the circumstellar magnetic field.

Since then, about 130 molecular species have been detected by radio astronomy spectroscopy in the interstellar medium and circumstellar envelopes. Thus, Shklovsky's [3] paper was at the origin of a large branch of modern radio astronomy.

4. Non-thermal galactic radio continuum and supernovae

In the early 1950s, Shklovsky was one of the first researchers to apply the synchrotron mechanism to the interpretation of cosmic radio emission, in the first instance to the Milky Way continuum background, which had been detected in 1931 by Karl Jansky. In [5], Shklovsky rejected the hypothesis about 'radio stars' that had been invoked to account for the Galactic background and instead put forward the mechanism of synchrotron radiation of cosmic-ray electrons in the Galactic magnetic field. The same idea occurred to him about the radio emission of the Crab Nebula; in [6], Shklovsky assumed that the entire spectrum of the Crab Nebula, from optical to radio wavelengths, could be explained by synchrotron radiation. This was soon confirmed after the detection of linear polarization of the Crab Nebula in the optical region. Then Shklovsky turned to historical supernovae; the first of the supernovae that he studied was that dating from AD 1054 which gave birth to the Crab Nebula. Following Shklovsky's suggestion, Chinese colleagues searched ancient chronicles, and this resulted in the establishment of the dates of the explosions for several supernovae now called historical (AD 1006, AD 1181, etc.). Shklovsky summarized his ideas on supernovae and their remnants in his monograph [7], which was supplemented in its second edition with a chapter on pulsars—a new class of radio sources, namely magnetized neutron stars remaining after supernova explosions. Shklovsky [8] also advocated the hypothesis that type I supernovae can be exploding white dwarfs that acquired mass from their companions in close binaries and thus lost stability by exceeding the Chandasekhar limit of $1.44M_{\odot}$. This explained the presence of supernovae in elliptical galaxies, where star formation ended long ago, and massive stars (progenitors of type II supernovae) appeared no longer.

5. Extragalactic astronomy and cosmology

Many of Shklovsky's studies have been dedicated to the problem of extragalactic radiation sources: Seyfert galaxies, active galactic nuclei, radio galaxies and quasars. Probably the most important, widely cited paper is about the variations in the flux of extragalactic radio sources. In [9], Shklovsky proposed and analysed in detail a mechanism of the variability of quasars and radio galaxies by episodes of ejection of clouds of relativistic particles from the nuclei of these objects. This enabled him to explain rather rapid variations on timescales of weeks. Other studies on extragalactic sources concern the optical spectra of quasars, the nature of radio jets in extragalactic radio sources, and many other topics.

Shklovsky was one of the first astrophysicists who responded to the discovery of cosmic microwave background (CMB) radiation by Penzias and Wilson in 1965. The term 'relic background', commonly used in the Russian-language literature as a synonym for CMB, was introduced by Shklovsky. In [10], Shklovsky interpreted the old observation dating from the late 1930s of interstellar optical absorption lines of CN molecules. Usually only resonant lines with the lower level being the ground level for a molecule are observed. However, in the case of CN, the lines from the first excited rotational level were detected, implying a noticeable population of this level in the interstellar medium. Shklovsky associated this fact with the excitation of CN by CMB quanta; interestingly this gave, via optical observations, an indirect estimate of the CMB radiation temperature, approximately 3 K. It turned out to be consistent with the temperature measured at longer centimetre waves, while millimetre waves ($\lambda = 2.64$ mm), corresponding to the first rotational transition of CN, were not yet accessible at that time.

6. Extraterrestrial life and intelligence

I.S. Shklovsky is one of recognized pioneers in the search for extraterrestrial intelligence (SETI). Following the paper by Cocconi and Morrison [11] on the possibility of communication with extraterrestrial intelligence (ETI) and on the frequency of the 21 cm hydrogen line as a natural standard, Shklovsky developed this idea in [12] and, much more profoundly, in his book [13]. This book was published in six editions (1962–2006) in Russian and in some other languages. An American version of it, with Carl Sagan as coauthor, appeared in 1966 [14]. Shklovsky analysed astronomical prerequisites for the origin of life in the Universe as well as the possibilities of life development to the intelligent level and of communicating with ETI. Negative results of many searches for ETI finally led him to the idea of the possible uniqueness of our civilization. He initiated the first scientific meetings dedicated to SETI (in Byurakan in 1964 and 1971, in Zelenchukskaya in 1975 and in Tallinn in 1981).

7. Shklovsky's science school

I.S. Shklovsky was an excellent teacher and an exigent supervisor for many scientists that graduated from the Astronomy Division of Moscow State University. His lectures attracted not only students but also researchers from all over Moscow and from other cities of our country. Among his disciples we can name such eminent astrophysicists as N.S. Kardashev, V.I. Slysh, V.G. Kurt, V.I. Moroz, P.V. Shcheglov, L.M. Gindilis, V.N. Kuril'chik, V.P. Grigor'eva, T.A. Lozinskaya, B.N. Panovkin, G.B. Sholomitskiĭ, V.F. Esipov, A.G. Gorshkov and M.G. Larionov. Shklovsky's books [1, 2, 7, 13–16] were and still remain classics in their field. The Radio Astronomy Department of the Sternberg Astronomical Institute and the AstroSpace Centre of the Lebedev Institute of Physics continue the tradition of research that was founded by I.S. Shklovsky.

8. Conclusion

It is difficult to enumerate in a brief review all the contributions made by I.S. Shklovsky. Among others, let us recall his paper on planetary nebulae [17]. In it, Shklovsky showed that a planetary nebula is a product of the evolution of a moderate-mass star of about a solar mass in the main sequence. At the end of its evolution such a star becomes a red giant with an extended convective zone and degenerate core. After several hundred thousand years of intense mass loss there remains a naked hot core (a white dwarf) and a surrounding ionized shell (a planetary nebula). This idea, quite novel at that time, has now been confirmed by numerous observational data and is generally accepted in the theory of stellar evolution. Shklovsky considered this [17] to be one of his best pieces of research.

A brilliant experiment proposed by Shklovsky and implemented by his co-workers was the so-called 'artificial comet' [18], a cloud of sodium released from the Soviet spacecraft Luna-2 during its flight towards the Moon. The cloud, which fluoresced under the action of solar radiation, was easily visible at a distance of more than 100 000 km from the Earth, and this made precise trajectory measurements possible. It was for this 'artificial comet' that Shklovsky was given the Lenin prize.

Also Shklovsky's work on the nature of X-ray sources [19], space research, aurora, nightsky glow in infrared lines of the OH molecule, dissipation of planetary atmospheres, origin of cosmic rays, etc., plus many popular articles on many subjects of astrophysics should be remembered. Shklovsky was an outstanding narrator. Many of the events of his life have been described in [20, 21]. The reference list quotes all the books written by I. S. Shklovsky and some of his outstanding papers. A complete bibliography of his works can be found in [22]. When preparing this report the author used materials from [22, 23].

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