Современная наука и инновации. 2025. № 4. С.127-133
ТЕХНИЧЕСКИЕ НАУКИ
ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ

Modern Science and Innovations. 2025;(4):127-133
TECHNICAL SCIENCE
INFORMATICS, COMPUTER ENGINEERING AND MANAGEMENT

Научная статья
УДК 523.62-337
https://doi.org/10.37493/2307-910X.2025.4.14

Изучение проблемы открытого магнитного потока по данным различных обсерваторий

Михаил Евгеньевич Сапралиев[1], Олег Николаевич Михаляев[2], Галина Алексеевна Манкаева[3*], Бадма Борисович Михаляев[4], Айса Дмитриевна Наминова[5]

[1, 2, 3, 4, 5] Калмыцкий государственный университет имени Б.Б. Городовикова (д. 11, ул. Пушкина, Элиста, 358000, Россия)
[1] m_sapraliev@mail.ru; https://orcid.org/0000-0001-7938-1659
[2] intotheelista@gmail.com; https://orcid.org/0000-0002-2816-6833
[3] mankaeva.galina@yandex.ru;
[4] bbmikh@mail.ru; https://orcid.org/0000-0002-9705-9804
*Автор, ответственный за переписку

Аннотация. ***Введение.*** Магнитное поле короны Солнца имеет прямое отношение к явлениям солнечной активности, в том числе к вспышкам и корональным выбросам массы. Оно также непосредственно связано с формированием постоянно исходящих потоков солнечной плазмы, называемых солнечным ветром. В частности, источники солнечного ветра концентрируются в областях так называемого открытого магнитного поля. Структура поля, расположение и форма его линий влияют на величину скорости потоков плазмы. В связи с этим большое значение приобретает проверка величины открытого магнитного потока, найденного с помощью расчетов, со значением, полученным из прямых наблюдений. ***Цель.*** Сравнить результаты расчетов магнитного потока с полученных данных из различных обсерваторий ***Материалы и методы.*** В настоящей работе проверка между данными проводится на основе фотосферных магнитных карт, построенных с помощью наземных телескопов, Кисловодской астрономической станции и GONG, в 2024 г. ***Результаты и обсуждение.*** Расчеты показали, что расхождение между наблюдаемым и расчетным открытым магнитным потоком значительное, характерное для максимума солнечной активности. ***Заключение.*** По всей видимости, точности потенциальной модели недостаточно для получения адекватного коронального магнитного поля, позволяющего учесть открытый магнитный поток в полной мере.
Ключевые слова: Открытый магнитный поток, физика плазмы, корональное магнитное поле, солнечная корона, магнитные карты фотосферы, Солнце
Для цитирования: Сапралиев М. Е., Михаляев О. Н., Манкаева Г. А., Михаляев Б. Б., Наминова А. Д. Изучение проблемы открытого магнитного потока по данным различных обсерваторий // Современная наука и инновации. 2025. № 4. С. 127-133. https://doi.org/10.37493/2307-910X.2025.4.14

Финансирование: Исследование выполнено в рамках госзадания Минобрнауки РФ № 075-03-2024-113
Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Статья поступила в редакцию 01.01.2025;
одобрена после рецензирования 01.02.2025;
принята к публикации 01.03.2025.

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Research article

Study of the problem of open magnetic flux based on the data from various observatories

Mikhail E. Sapraliev[1], Oleg N. Mikhalyaev[2], Galina A. Mankaeva[3*], Badma B. Mikhalyaev[4], Aisa D. Naminova[5]

[1, 2, 3, 4, 5] Kalmyk state university named after B.B. Gorodovikov (11, st. Pushkin, Elista, 358000, Russia)
[1] m_sapraliev@mail.ru; https://orcid.org/0000-0001-7938-1659
[2] intotheelista@gmail.com; https://orcid.org/0000-0002-2816-6833
[3] mankaeva.galina@yandex.ru;
[4] bbmikh@mail.ru; https://orcid.org/0000-0002-9705-9804
*Corresponding author

Abstract. ***Introduction.*** The magnetic field of solar corona is directly related to solar activity, including flares and coronal mass ejections. It is also directly linked to the formation of the constantly outgoing streams of solar plasma, known as the solar wind. Specifically, solar wind sources are concentrated in regions of the so-called open magnetic field. The structure of field, location, and shape influence the speed of the plasma streams. Therefore, it is crucial to compare the calculated open magnetic flux with the value obtained from direct observations. ***Goal.*** Compare the results of magnetic flux calculations with the data obtained from various observatories ***Materials and methods.*** In this paper, the data validation is carried out using photospheric magnetic maps constructed using ground-based telescopes, the Kislovodsk Astronomical Station and GONG, in 2024. ***Results and discussion.*** Calculations have shown that the discrepancy between the observed and calculated open magnetic flux is significant, typical for the maximum of solar activity. ***Conclusion.*** Apparently, the accuracy of the potential model is not sufficient to obtain an adequate coronal magnetic field that would allow the open magnetic flux to be taken into account fully.
Key words: Open magnetic flux, plasma physics, coronal magnetic field, solar corona, photospheric magnetic maps, Sun
For citation: Sapraliev ME, Mikhalyaev ON, Mankaeva GA, Mikhalyaev BB, Naminova AD. Study of the problem of open magnetic flux based on the data from various observatories . *Modern Science and Innovations*. 2025;(4):127-133. (In Russ.). https://doi.org/10.37493/2307-910X.2025.4.14

Funding: The study was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation No. 075-03-2024-113

Conflict of interest: the authors declare no conflicts of interests.

The article was submitted 01.01.2025;
approved after reviewing 01.02.2025;
accepted for publication 01.03.2025.

Introduction. Open magnetic fields on the Sun are characterized by the fact that the field lines originate on its surface (the photosphere) and extend far into space. Their study is important because they reveal the large-scale structure of the solar magnetic field and form stable connections between the Sun and the interplanetary medium, determining the geometry of the solar wind flow, as well as its sources on the Sun [1]. Systematic studies of the open field began with the construction of simple potential models of the field in the corona [2-4] based on maps of the photospheric field, initially obtained using ground-based observations [5-6]. The Wilcox observatories are widely known Solar Observatory (WSO) in the United States, an international network of ground-based observatories Global Oscillations Network Group (GONG), as well as the Kislovodsk Mountain Astronomical Station, where the Solar Telescope for Operational Forecasts (STOP) is installed. Currently, solar magnetic field observations are conducted using magnetographs installed on spacecraft, such as Solar Dynamics Observatory (SDO). The OMNI spacecraft observe the interplanetary field at a distance of 1 AU. The aim of this work is to study the problem of open magnetic flux (OMF) and to verify the results using data from the Global observatories.

Oscillation Network Group (GONG) and the Kislovodsk Mountain Astronomical Station (GAS GAO) of the Russian Academy of Sciences .

Materials and methods of research. Direct observation of the interplanetary field allows us to test open field models for their agreement with observational data. The main criterion for testing is the magnitude of the total magnetic flux of the open field. In this case, the field of different directions, from the source and to the source, is taken into account. The magnetic flux calculated in this way is called unsigned. The first measurements until about 1997 showed good agreement between the average model values of the field strength calculated using coronal models (Potential Field Surface , PFSS and MHD) [7-8], which use identical input maps of the photospheric magnetic field and observations in situ at a distance of 1 AU [9-11]. However, later observations revealed a discrepancy, and over the next two decades, model and in- obtained In situ unsigned open flux values have not been consistent and show discrepancies reaching a factor of 2 or more during solar maximums. Currently, heliospheric scientists are noting the existence of a missing flux problem. Proposed sources of the missing flux include, for example, problems with photospheric magnetic field measurements [12], incorrect estimates of the polar magnetic field [13], unaccounted for magnetic fields from coronal mass ejections, as well as the time-dependent nature of the magnetic field and the methodologies for estimating the total open flux from in situ observations. Arge *et al* . [11] suggest that the boundaries of coronal holes observed in the extreme ultraviolet are merely the boundaries of a long-term open field. Beyond these boundaries, and in the region of the apparently closed field, there is a layer of a constantly evolving mixture of open and closed fields with a width of about one or two supergranules.

Sun service is used to perform coronal field calculations. Gazers [14], using data from the Kislovodsk Mountain Astronomical Station. A PFSS model of the coronal field is constructed using photospheric magnetic field maps obtained from magnetograph observations. The coronal field is constructed similarly using GONG magnetic maps. Magnetic field lines are traced in two directions, from the solar surface to the source surface and vice versa. This allows for the magnetic flux to be fully accounted for. Field lines emanating from the solar surface, i.e., "outward" lines, and those entering the solar surface, i.e., "inward" lines, are considered. Thus, the total field flux is taken into account, regardless of its direction, or the unsigned magnetic flux.

Results and discussion. The most plausible reason for the discrepancy in the MPE calculations is the inaccuracy of the coronal field models calculated from photospheric maps, of which there are several. As noted above, the simplest of these is the PFSS model of a potential field with a radial direction on the source surface. Although the most accurate and complex dynamic MHD models will be required to finally reconcile theory and data, it is worth noting that PFSS models, such as WSA, with all the permissible simplifications, remain extremely effective for studying and understanding the complex relationship between the Sun and the heliosphere. In this paper, we verify the results of the MPE comparison using data from the Global observatories. Oscillation Network Group (GONG) and the Kislovodsk Mountain Astronomical Station of the Main Astronomical Observatory of the Russian Academy of Sciences. The validity of this hypothesis is further confirmed by comparing the morphology of coronal holes obtained by PFSS magnetic line tracing with coronal holes observed in ultraviolet light using the Atmospheric Imaging Assembly on board the Solar Dynamics Observatory (AIA / SDO) ultraviolet telescope.

For comparison, Figure 1 shows an image of a large coronal hole obtained on February 1, 2024, in the 193 Å line with the SDO / AIA ultraviolet telescope. The coronal hole serves as an indicator of a large open-field region, constructed from the GONG map, marked in red. The locations of the coronal hole and the open-field region coincide with minor variations. Figure 2 shows an example of the calculation of the open coronal magnetic field obtained from the GONG photospheric maps.

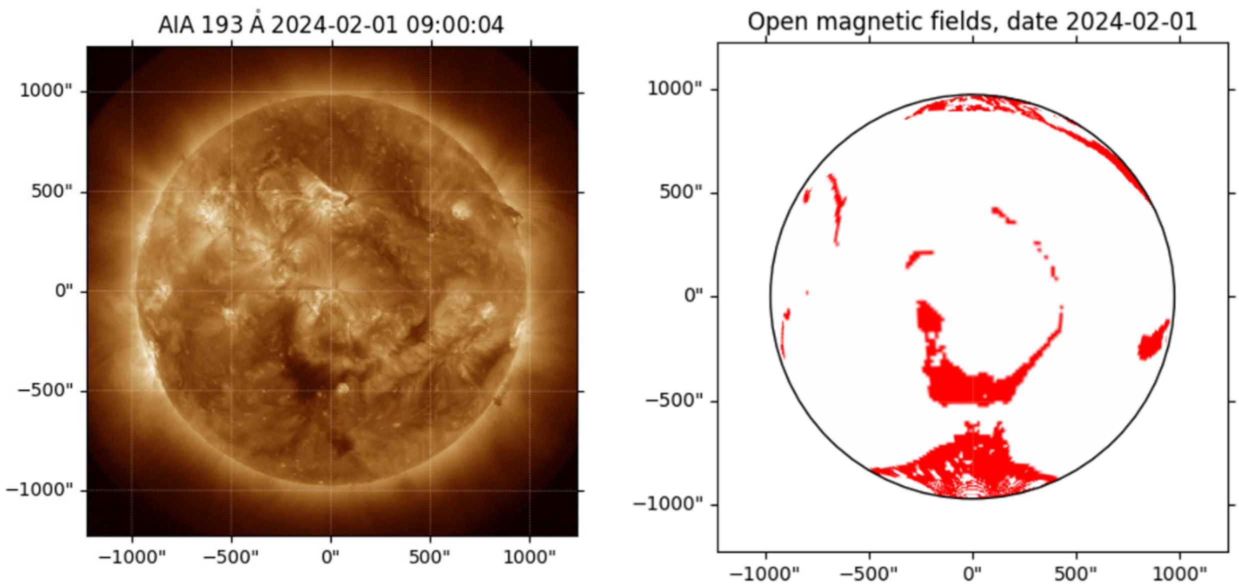

Fig. 1- A coronal hole image obtained with AIA / SDO (left). An example of an open-field region on the photosphere obtained from GONG data (right).

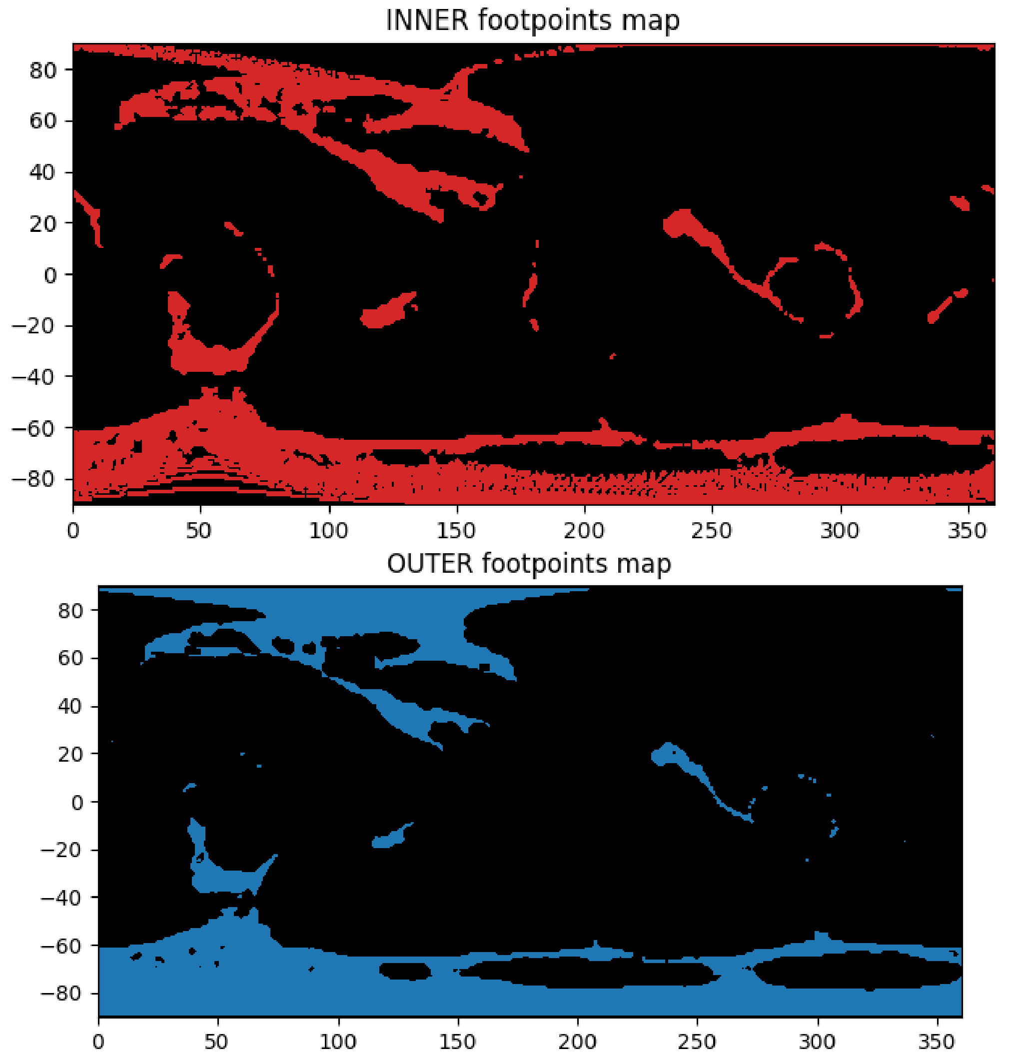

Fig. 2 - Open field on the photosphere obtained from GONG data .
Tracing magnetic field lines inward (top) and outward (bottom). There are slight discrepancies, indicating incomplete data from each individual measurement.

Figure 3 shows the results of a study of the behavior of the NMF during the year and a half of the maximum of the last solar cycle. The black line shows the NMF values obtained from direct observations, while the red and blue lines show the NMF change calculated by the PFSS model based on photospheric maps from the Kislovodsk Astronomical Station and GONG. There is a significant discrepancy between the observational data and the model calculations, characteristic of solar maximums. The data from the Kislovodsk Astronomical Station provide slightly better results than those from GONG.

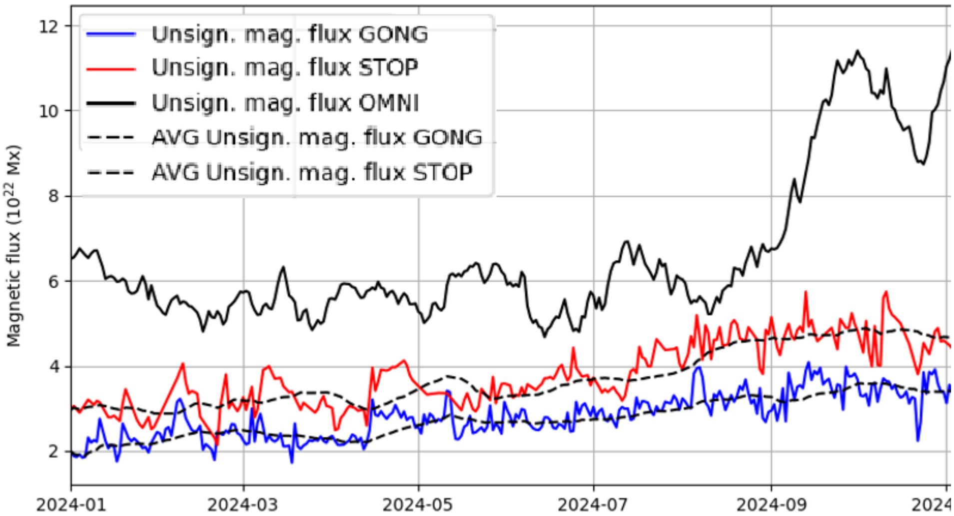

Fig. 3 - Change in the open magnetic flux during the last solar activity cycle according to OMNI data (direct observation), the STOP magnetograph (Kislovodsk Astronomical Station), and GONG. The vertical axis shows the OMF values obtained by direct observation or using the coronal field model.

Conclusion. The solar magnetic flux estimated using the PFSS model was studied using ground-based observations from the Kislovodsk Astronomical Station and GONG. The results show a significant discrepancy with direct spacecraft observations, typical during periods of solar maximum. Apparently, the accuracy of the potential model is insufficient to obtain an adequate coronal magnetic field that would fully account for the NMF. Conclusion: MHD models are necessary for constructing the coronal magnetic field used in solar wind modeling.

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Информация об авторах

Сапралиев Михаил Евгеньевич – младший научный сотрудник Калмыцкого государственного университета

Михаляев Олег Николаевич – младший научный сотрудник Калмыцкого государственного университета

Манкаева Галина Алексеевна – старший преподаватель кафедры теоретической физики Калмыцкого государственного университета

Михаляев Бадма Борисович – доктор физико-математических наук, доцент, заведующий кафедрой теоретической физики Калмыцкого государственного университета

Наминова Айса Дмитриевна – инженер - исследователь Калмыцкого государственного университета

Вклад авторов: все авторы внесли равный вклад в подготовку публикации..

Information about the authors

Mikhail E. Sapraliev – Junior Research Fellow Kalmyk State University
Oleg N. Mikhalyaev – Junior Research Fellow Kalmyk State University
Galina A. Mankaeva – Senior Lecturer, Chair of Theoretical Physics Kalmyk State University
Badma B. Mikhalyaev – Dr. Sci. (Phys.–n-Math.), Associate Professor, Head of Chair of Theoretical Physics Kalmyk State University
Aisa D. Naminova – Research engineer Kalmyk State University

Contribution of the authors: the authors contributed equally to this article.