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Solar Activity Observations at the World Data Center for Solar–Terrestrial Physics

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Abstract—Experimental data on solar activity are now used widely in basic and applied research to investigate phenomena occurring on the Sun and in interplanetary space and to understand their effects on processes in Earth's outer and inner shells. The most valuable data come from multiyear observations. The World Data Center for Solar–Terrestrial Physics in Moscow has a representative collection of observations obtained by the global network of solar and astronomical observatories and with instruments onboard spacecraft. This article describes solar activity data stored in the center's repository and published on its website in the public domain. The center undergoes continual improvement through the use of new information technologies providing free and convenient data access and data citation opportunities and is constantly expanding its information resources available on the Internet.

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1. INTRODUCTION

Modern scientific research relies on comprehensive analysis of large volumes of data from various fields of science and on the application of modern computer methods for data processing, analysis, and interpretation. The World Data Center for Solar–Terrestrial Physics (WDC for STP) in Moscow provides free access to large data arrays, long series of observations, and a unique and representative collection of national and foreign data on solar–terrestrial and space physics, including observations of solar activity and interplanetary magnetic field (IMF).

The WDC for STP was established in 1956. At that time, preparations began for a major science project of the 20th century, the International Geophysical Year (IGY), held in 1957–1958. The project was attended by scientists from 67 countries. The tasks of conducting planetary geophysical research within the project and achieving progress in the most promising areas of geophysics were pursued by creating planetary networks of observation stations: geomagnetic, ionospheric, seismological, meteorological, etc. This initiative was accompanied by creating a system of World Data Centers (WDCs). By decision of the International Council of Scientific Unions (ICSU) and the World Meteorological Organization (WMO), in agreement with the governments of several countries, two universal centers, WDC A in the United States and WDC B in the Soviet Union, were established to collect IGY data for the entire complex of observations, together with specialized WDC C in several countries, which focused on data from one section of the IGY program. WDC B comprised several centers, one of which is the WDC for STP in Moscow.

The WDC system ensured accumulation and long-term guaranteed storage of data as well as free access for researchers and academics. The centers collected and exchanged data by specifically designed rules, which were formulated in the *Guide to International Data Exchange through the World Data Centers* [1]. Specific types of observations for data collection and specific data presentation forms were defined. Periodically, the centers published catalogs of data availability in the WDCs [2].

When the IGY came to an end, the WDC system was retained for collecting, long-term storage, and dissemination of data obtained by observation networks and during the implementation of geophysical projects such as the International Year of the Quiet Sun (1964–1965), International Year of the Active Sun (1969–1971), International Magnetospheric Study (1976–1979), International Solar Maximum Year (1979–1981), and other international programs and experiments. For over 60 years, the results of various international and national geophysical projects and programs as well as the results of observations at stations and observatories, ships, drifting stations, airplanes, satellites, etc., have been collected and stored at the WDCs [3].

The 29th General Assembly (2008) of the International Council for Science adopted a resolution to

establish a new body, the World Data System (WDS, http://www.icsu-wds.org/), to combine all the accumulated data into a single body and develop data storage methods and technologies that would ensure information safety and data access both today and in the distant future. A transition was made from a multitude of isolated WDCs and Federation of Astronomical and Geophysical Data Analysis Services (FAGS) to a global interoperable distributed data system with developed interconnections between individual disciplinary components, with a broader disciplinary and geographical base, and with interdisciplinary applications for data processing. To date, the WDS has over 70 regular members. The WDS Portal, now under construction, will combine information resources of all system members. The WDC for STP has been a regular member of the WDS since 2012, follows the basic principles of the WDS Constitution, and supports the WDS Data Policy [4].

Currently, the WDC for STP repositories contain substantial amounts of planetary geophysical data collected in our country and abroad, supported by modern data management and access technologies. The center provides data to research institutes, organizations, and individuals for basic and applied research and to educational institutions for educational purposes without any restrictions and free of charge. The WDC for STP website http://www.wdcb.ru/stp/index.en.html provides information about the center, user information, data availability catalogs, and free on-line access to the data.

The WDC for STP has an archive of historical and modern global observations, which contains data on Earth's magnetosphere (field and particle measurements in the magnetosphere, records of geomagnetic field variations, and tables of hourly mean values and geomagnetic activity indices), Earth's ionosphere (ionospheric radio sounding data obtained from Earth's surface and from satellites, data on ionospheric absorption of radio waves, structural characteristics of the ionosphere, and radio noise measurements), and cosmic rays (data on solar and galactic protons, neutrons, and mesons; data from neutron monitors, meson telescopes, and ionization chambers). A separate section of the archive presents data on solar activity and IMF.

2. SOLAR ACTIVITY DATA

The WDC for STP repositories contain historical observational data on solar phenomena from the global network of solar and astronomical observatories for the period from 1957 to the beginning of the 1990s, stored in the form of paper documents: tables, solar maps, etc. These are data on sunspot numbers, sunspot groups and their areas, calcium floccules, solar magnetic fields, solar filaments from observations in the Hα line, and mass ejections. Also, they contain synoptic and photographic maps of the Sun, optical observations of the solar corona, observations of flares in the Hα line and patrol observations of solar activity, measurements of the total solar radio flux, fixed frequency observations of prominent solar phenomena and radio bursts, east–west radio scans of the solar disk, and radio spectrograms of solar events.

Together with the exchange of observatory data, the WDCs exchanged publications containing special data compilations and information of interest to researchers. The publications served many WDC users. The publications included *Solar–Geophysical Data*, a monthly bulletin published by the US National Geophysical Data Center from 1955 to 2009. The bulletin contains comprehensive collections of various types of observational data on solar activity and its effects on the Earth as well as information on major solar events and on Sun-related interplanetary, ionospheric, and other geophysical effects. The center also contains *Upper Atmosphere Geophysics (UAG)* Reports, a series of reports published by the US National Geophysical Data Center from 1968 to 1996, with collections of solar, interplanetary, and geophysical data for selected time intervals. These include special catalogs on active solar phenomena (flares, coronal holes, and solar filament eruptions), collections of observational briefs with primary processing of individual outstanding solar events, their responses in interplanetary environment and near-Earth space, which are of particular interest to the scientific community. The WDC for STP in Moscow also issued a series of publications entitled *World Data Center B Materials* with datasets on various manifestations of solar activity.

Over time, new observation methods appear, and changes take place in technologies for collecting observations and for processing, transmitting, and storing information, including presentation of data. With the advent of tools with computer recording, the WDCs began to exchange data in machine-readable form, i.e., as data files accompanied by format description and explanatory text, recorded on various kinds of media (magnetic tapes, diskettes, CDs). In the 1980s, unified international formats were introduced for data presentation in machine-readable form to unify data exchange procedures. The center began to develop electronic data archives and computer databases. The next large array of historical data stored at the WDC for STP consists of data sets in machine-readable form (electronic form). All of them are available on the center's website.

New data on solar activity were obtained using instruments onboard artificial Earth satellites (AES): observations of solar radiation fluxes in the Lα radiation line (Lyman alpha), collected onboard the *Explorer* satellite in 1982–1989; observations in the extreme UV range onboard *Explorer-E* in 1977–1980; and in the soft X-ray range (1–8 Å) onboard *Solrad* in 1968–1974 and the *GOES* geostationary satellite.

AES also measure total solar radiation, i.e., energy emitted by the Sun at all wavelengths. The center stores measurement data on Earth's radiation above the atmosphere, which were obtained using a cavity pyrheliometer onboard the *Nimbus-7* satellite (1978–1989) and the solar radio emission measurements made onboard the *Solar Maximum Mission* orbital station (1980–1987).

A data array with mean hourly parameters of the solar wind and IMF magnitudes was compiled using data from several satellites by Dr. J.H. King at NASA's Goddard Space Flight Center (NASA GSFC) and handed over to the WDC for STP on behalf of the National Space Science Data Center and WDC on rockets and satellites.

At the same time, ground-based observational data appeared in machine-readable form, which are now stored at the center and available for use:

—Coronal index of solar activity, which characterizes the total radiation energy of the Sun's outermost atmospheric layer (corona) at a wavelength of 530.3 nm, derived from photometric patrol observations in 1964–1986 at eight ground stations.

—Data on relative sunspot numbers in the international (Zurich) system: maxima and minima; daily, monthly, annual, and smoothed values over the entire observation period. Daily reports on sunspot numbers from the Greenwich Observatory (1874–1982) and the astronomical observatories of Rome (1958–1990) and Taipei (1964–1992). Sunspot group reports from the astronomical observatories Mount Wilson (1967–1989), Rome (1978–1990), Greenwich (1875–2018), Catania (1978–1987), and the US Sun Service (1981–2018).

—Solar flares from observations in the strongest H-alpha hydrogen spectral line (1938–1994), a complete list of flares from patrol observations (1955–1994), and a comprehensive flare index (CFI) calculated for all major flares in 1955–1980.

—Measurements of radio noise at ground stations (1960–1989) and of spectral radio noise (1967–1989).

—Observations of calcium floccules (chromospheric faculae) obtained at solar observatories Hale (1979–1981), Big Bear (1981–1987), and McMath (1942–1979).

—Measurements of the Sun's magnetic field (Sun as a Star) summed over the solar disk (magnetic field intensity in μT). Each value is a weighted average of all measurements throughout the day. Data from the Crimean Astrophysical Observatory from 1968 to 1976 and the Stanford Solar Observatory from 1975 to 1989.

—Solar radiation density data recorded at a frequency of 2800 MHz with a radio telescope near Ottawa (1947–2018) in the form of tables containing observed, corrected, and absolute flux values averaged over daily, monthly, and annual intervals. These data were prepared at the Herzberg Institute of Astrophysics (Canada).

Most data collections in the current repositories of the WDC for STP are constantly replenished, and new collections are compiled in electronic format. The most frequently used data are now freely available on the center's webpages in the section Solar Activity (www.wdcb.ru/stp/solar/).

One of the most popular solar activity indicators (indices) is the relative sunspot number (Wolf number). The site contains data on sunspot numbers: daily total sunspot number since 1818, monthly mean total sunspot number since 1749, and yearly mean total sunspot number since 1700. These data are provided by the World Data Center for the Production, Preservation and Dissemination of the International Sunspot Number (WDC-SILSO, Royal Observatory of Belgium, Brussels). On June 1, 2015, this center introduced a new version of the data series (version 2.0), which enhances the impact of sunspot groups and smoothed (according to the authors) inhomogeneities in the time series (http://sidc.oma.be/silso/newdataset).

Another solar activity index, crucial for many studies, is the solar radio emission flux with a wavelength of 10.7 cm (2800 MHz), which correlates well with changes in solar activity throughout the visible solar disk. The website users are provided with daily, monthly, and yearly series of the radio emission flux, measured with a solar radio telescope, in three forms: observed values, those corrected for the change in the Earth–Sun distance and reduced to an average distance, and absolute values. These data are published by the Radio Observatory in Penticton (British Columbia, Canada).

The website users can check out the solar cycle table, which shows the year of beginning, years of maximum and minimum, relative sunspot number smoothed over 13 months, cycle length, lengths of the growth and decline branches, and a description of features of current cycle 24. The website also presents catalogs of solar flare events in cycles 23 and 24 with an X-ray score greater than M1. Flares reflect the energy of the corresponding magnetic fields, and the behavior of flare parameters in the 11-year cycle is of considerable interest. The catalog contains for each flare: the time parameters, X-ray and optical (in Hα lines) score, integral X-ray flux, coordinates (heliographic latitude and Carrington longitude), active region where the flare occurred, peak radio flux at selected frequencies, dynamic radio bursts, coronal mass ejection, time and maximum hard X-ray energy, and maximum solar protons flux and related dynamic phenomena in the optical range.

The website contains electronic versions of six catalogs of solar proton events (SPEs) and their energy spectra, which were compiled by teams of solar–terrestrial physicists and edited by Yu.I. Logachev. The catalogs include systematic data for 1970–2008 on

proton generation events for which the maximum flux protons with an energy of $Ep > 10$ MeV exceeded $1\ cm^{-2} \cdot s^{-1} \cdot sr^{-1}$ (pfu) and contain information about the particle sources and the electromagnetic radiation associated with a given event throughout the observable range. For each event, the catalogs provide the integral energy spectrum and the tables and graphs of recorded proton fluxes from various spacecraft (for SPEs of 1996–2008) at the maximum of the time intensity profile.

The data on the sectoral structure of the IMF include tables containing daily determinations of IMF polarities, either away from Sun or toward the Sun (sector's sign), from the data provided by Stanford University (1947–1975) and from observations at the Vostok and Tule observatories (1974–2010); L. Svalgard's table containing the most likely times of passage of the IMF sector boundary, when the IMF polarity is reversed; the table and corresponding graph containing IMF azimuthal angles calculated from daily averages of hourly X and Y components from the NASA GSFC data.

3. DEVELOPMENT OF THE WDC DATA MANAGEMENT SYSTEM

Over the lifetime of the WDCs, significant development has taken place in data management technology, with the transition from simple, library-type archives to modern network data presentation technology, from data availability catalogs to on-line data releases and development of thematic databases and portals. The WDC for STP undertakes continual effort to improve the methods of storing, organizing, and disseminating large arrays of geophysical data, ensuring free network access to them.

The center's website (http://www.wdcb.ru/stp/index.en.html), active since 1995, is part of a global distributed information resource system for geophysics. A system of links provides access to data posted on the websites of other centers, institutes, scientific organizations, and individual researchers.

Since 2014, the WDC for STP has been implementing the Old Data Storage Project to transfer data from paper to electronic form. The goal of the project is to increase data arrays in electronic form, prevent the loss of valuable historical data, and ensure free Internet access to them for more efficient use.

The second important project is the development of a modern system for recording, publishing, and citing geophysical data with assignment of a digital object identifier (DOI); the Earth Science Database. Today, significant changes have taken place in attitudes towards data, their dissemination, citation, and documentation. Obtaining new data is treated as a full-fledged scientific result, subject to dissemination and citation like all other scientific information sources (journals, articles, or books). The DOI system is extending vigorously into scientific data, including solar and geophysical observations. A dataset with an assigned DOI index becomes more accessible for search, identification, and citation.

Data are registered and published with assignment of a DOI via Crossref. A central repository has been established, which stores a metadatabase of all registered databases and datasets, including full data descriptions, information about authors and producers, data suppliers and data publishers, and other information that may be useful to consumers. Each registered object has a response page with complete information about the database/dataset, data location address, and a sample citation.

For example, the database of six SPE catalogues, as well as each catalogue separately, was assigned a DOI registered with Crossref. Response pages were created for the database and for each catalogue. From the response pages, one can go via the data download addresses, to the datasets published on the website of the WDC for STP.

CONCLUSIONS

By preserving historical data sets, complementing them with new observations, and improving the data management system, the World Data Center for Solar-Terrestrial Physics seeks to provide scientists with easy and convenient access to the data, increase the value of scientific data, and create conditions for fuller use.

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