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Hot Jets in the Solar Corona: Creating a Catalogue of Events Based on Multi-Instrumental Observations

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Abstract—We present a catalogue of solar coronal plasma jets with a temperature above 0.5 MK, which includes primary information about the events, parameters of the diagnosed jets, as well as related eruptive phenomena. The catalogue (https://solar.sao.ru/coronal-jets-catalog/) contains data obtained using the spaceborne EUV high-precision telescope SDO/AIA and ground-based radio telescopes and spectrometers, including RATAN-600, SRH and NoRH. For a number of events data on the reconstructed magnetic field is also presented. The purpose of the catalogue is to provide summary information on coronal jets for further statistical analysis, determination of characteristic parameters of jets, and for in-depth study of the individual events by all interested researchers.

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1. INTRODUCTION

The study of plasma jets in the solar atmosphere is an actively developing scientific field both in the context of fundamental plasma physics and in the field of plasma astrophysics (e.g., Shen, 2021). This research is also of great importance for the development of methods for predicting space weather. Coronal jets are phenomena regularly observed on the Sun at all phases of the solar activity cycle, both in the quiet Sun and in coronal holes and active regions.

Collimated jet-like structures with temperatures above the transition zone temperature, which distinguishes them from spicules and macrospicules, are often reported in the X-ray and extreme ultraviolet (EUV). The data obtained over the past three decades by various space missions such as Yohkoh, SOHO, STEREO, Hinode, SDO, and IRIS (Raouafi et al., 2016; Shimojo et al., 1996; Shimojo and Shibata, 2000; Musset, 2020) have provided an extensive material for studying the origin, morphology, and evolution of coronal jets. Despite significant advances in both observational and theoretical research, the underlying physical mechanisms that trigger, support, and control these events, as well as influence their evolution, remain unclear (McGlasson et al., 2019; Wyper et al., 2019; Yang et al., 2019; Joshi et al., 2020; Huang et al., 2020; Sterling and Moore, 2020).

Present-day research is based on the use of data from the newest space and ground-based telescopes, obtaining both, the spectral and imaging characteristics of the object, which makes it possible to study a wide variety of jet flows present in the Sun's atmosphere. Simultaneous observations of plasma jets in several bands of the electromagnetic spectrum allows us to study in detail their origin, energy, dynamics, and collimation, as well as the fundamental plasma processes associated with them: instability, turbulence, and acceleration of charged particles. We have developed a catalogue of hot jets in the solar corona with the purpose of providing a summary of multi-wavelength information for further statistical analysis, determining the characteristic parameters of the jets, and for further in-depth study of individual events presented by all interested researchers. The paper describes the structure of the catalogue, provides examples of the obtained data, and discusses prospects of using the catalogue data for solving open coronal jet problems. The catalogue is available on the website of the Russian Special Astrophysics Observatory (St. Petersburg branch) (https://solar.sao.ru/coronal-jets-catalog/).

2. CONTENT OF THE CATALOG

2.1. Primary Information

The catalogue contains information about the date and time of the jet, heliographic coordinates, dura-

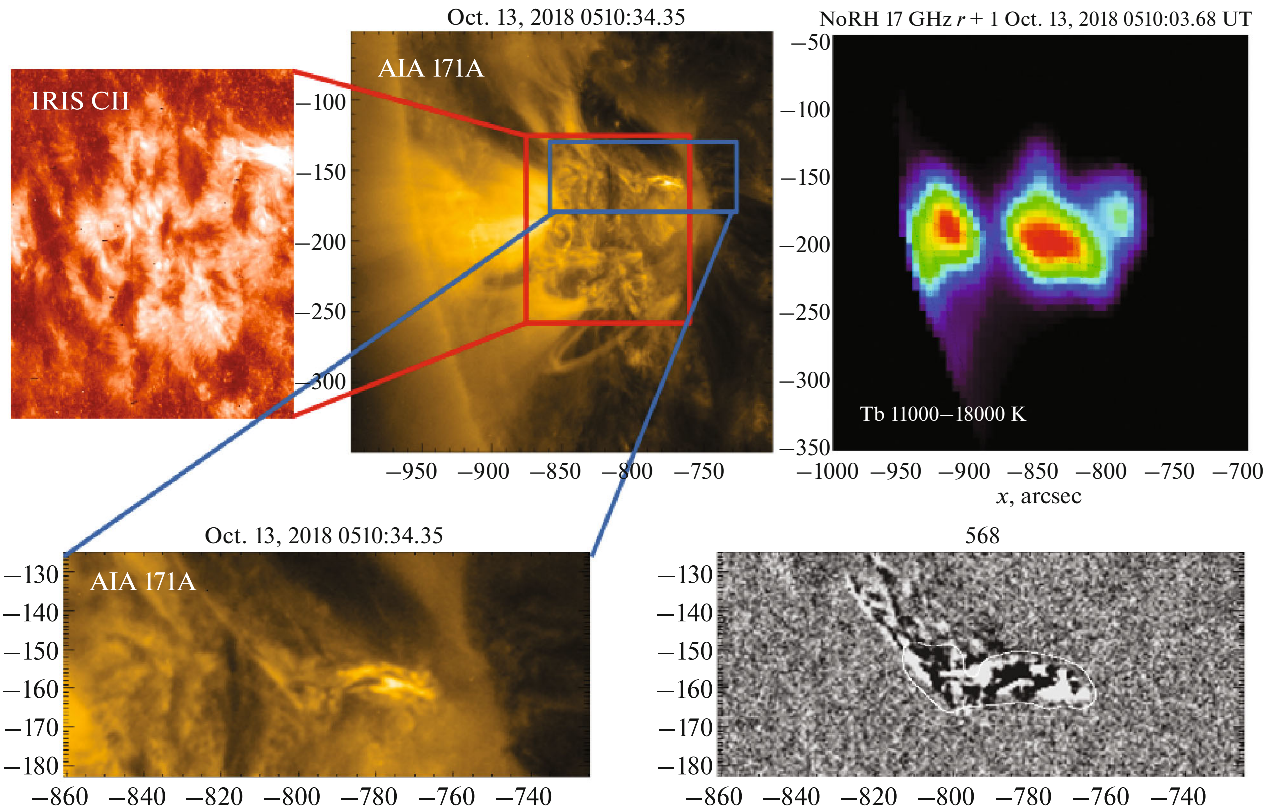

Fig. 1. Top row: images of AR 12724, obtained on December 13, 2018 0510 UT with the instruments: IRIS, CII (left), SDO/AIA, 171 Å (center), and NoRH, 17 GHz (right). Axes marks are in arcseconds. Bottom row: a closer look at the jet, in the 171 Å filter from SDO/AIA (left), and the corresponding running difference (right). White contour outlines the jet boundaries detected by the algorithm.

tion, as well as data on the associated flare, radio burst, and coronal mass ejection, if they were observed. Information about observation time and primary coordinates of coronal jet candidates are taken from the database of events and objects on the Sun Heliophysics Events Knowledgebase (HEK, https://www.lmsal.com/hek/index.html). Context information is added for each event by means of corresponding links to https://solarmonitor.org and to Solar and Geophysical Event Reports provided by the Space Weather Prediction Center.

2.2 Microwave Observations

We complemented the catalogue with associated microwave data from the ground-based instruments: the RAtan astronomical Telescope of the Academy of Sciences (RATAN-600), the 48-antenna prototype of the Siberian radio heliograph (SRH) and the Nobeyama radio heliograph (NoRH).

Thus, full-disk images of the Sun at 1.76 cm (17 GHz) in intensity and polarization, obtained with the NoRH radio heliograph (Nakajima et al., 1994) in a time interval of about an hour or more, covering the jet lifetime, are added to the catalogue. The radio maps are taken with a 10-minute cadence and have a spatial resolution of about 10 arc seconds at 1.76 cm. For a number of events, time sequences of regional maps with a time step of 1, 5, or 10 seconds at frequencies of 17 and 34 GHz are also constructed. An example of the resulting images of the region containing a jet at 17 GHz is shown in Fig. 1 together with the images in other spectral bands. In addition to the bright radio sources above the active region, the 17 GHz intensity map also localizes the area of increased radio emission directly associated with the jet ejection zone.

Spatially resolved information about microwave radiation in the 4–8 GHz band was obtained using the SRH (Lesovoi et al., 2017). This instrument provides two-dimensional radio images of the Sun at 5 (during years 2016–2017) or 32 (starting from 2018) frequencies in the 4–8 GHz band with a 10-second cadence. Despite the low spatial resolution (~30 arc seconds at a frequency of 6 GHz), if variation of radio brightness is observed, it is possible to determine an active region that the jet originates from, and thereby confirm that the changes in the microwave radiation is indeed associated with the jet. An example of observing a jet with SRH is shown in Fig. 2. In this case, an increase in radio brightness at all five frequencies (Fig. 2, right)

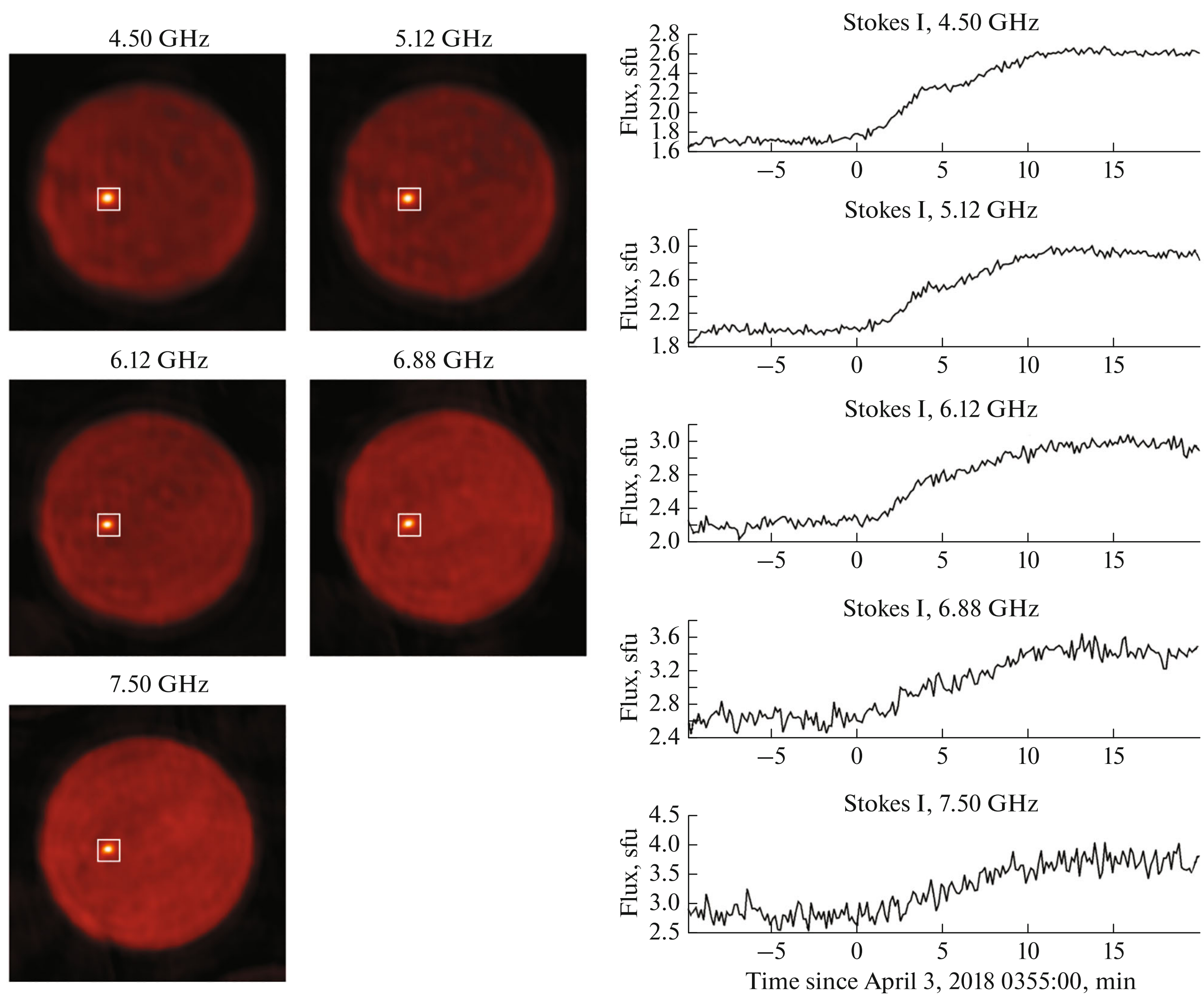

Fig. 2. SRH jet observation on April 3, 2018. Left: radio maps at 5 frequencies: 4.5, 5.2, 6.0, 6.8 and 7.5 GHz. White rectangle outlines the active region where the coronal jet is observed. Right: microwave fluxes from the outlined region. Zero time corresponds to 0355 UT, when first signs of jet formation were detected in the SDO/AIA images.

was observed, which coincides with the first signs of the appearance of the jet in the SDO/AIA EUV images, and the radio source is located in the same active region where the jet was observed. Thus, the analysis of simultaneous observations in the EUV and radio allows us to conclude that the observed increase in radio brightness is directly related to the process of the jet initiation.

Spectral-polarization data in the 3–18 GHz band are provided by observations with RATAN-600 (Bogod, 2011), which were added to the catalogue of events that coincide in time with the RATAN-600 observations. For jet research, RATAN-600 data can be useful, for example, for estimating the spatial (one-dimensional, up to 18 arc secs) and spectral (with a frequency resolution of up to 1%) structure of the active region in which jets occurred. Spectral-polarization data allow us to make estimates of the magnetic field. Multi-azimuth observations give an idea of the evolution and dynamics of the active region with a time step equal to the time between observations in azimuths (from 8 to 40 minutes). For several events this is enough for changes in intensity and polarization to be noticeable. An example of an active region in which a jet and other small active process occurred is shown in Figs. 3–5. However, for a detailed study of the fast processes of jet initiation and evolution the effective RATAN-600 time resolution is obviously insufficient. Higher time resolution of RATAN-600 is expected in the future after the introduction of new modes into regular observations: tracking mode and multiple scanning, which are currently being tested (Storozhenko et al., 2020).

Microwave observations provide important context information about the active regions in which plasma jets were observed, and in some cases also make it pos-

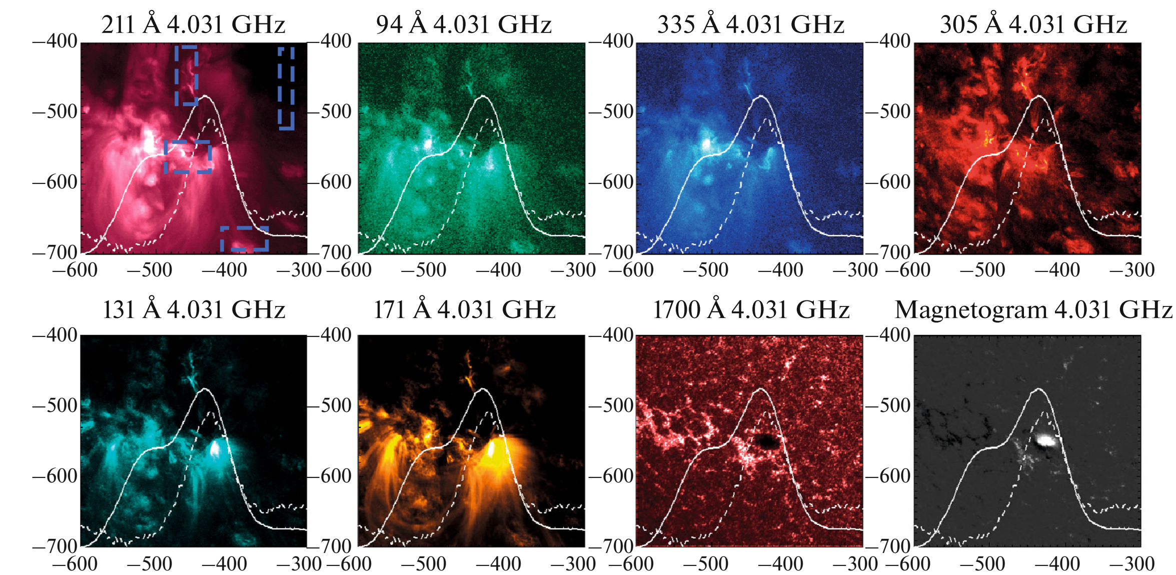

Fig. 3. Images of AR 12681, obtained on September 23, 2017 0832 UT (AIA) and 0833 UT (HMI) superimposed with the antenna temperature from the RATAN-600 scans Ta (intensity, I, and polarization, V), observed at 0832 UT at the frequency of 4.031 GHz. Axes are in arcseconds. Weak activity, detected during UT 0715–0915 in different emission lines, is shown on the top-left image with blue rectangles. Images were rotated so that the long axis of the RATAN-600 beam is vertical.

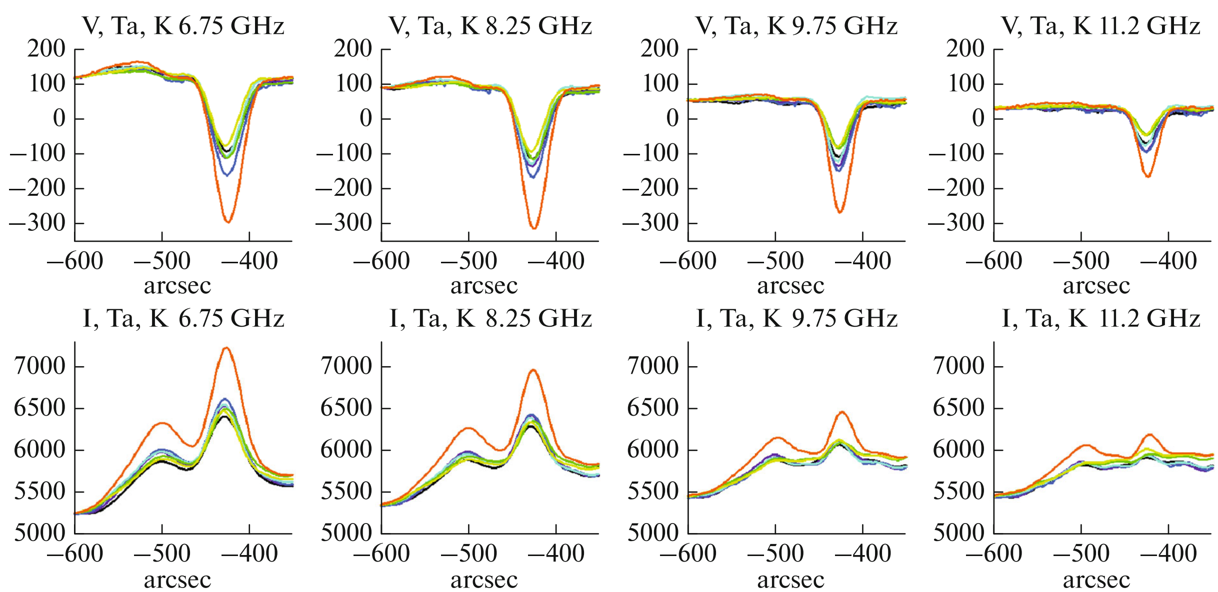

Fig. 4. The RATAN-600 scans of antenna temperature (in K) of AR 12681, observed on September 23, 2017 at the frequencies 6.75, 8.25, 9.75, and 11.20 GHz. Top row: Stokes V (polarization), bottom row: Stokes I (intensity). Different colors correspond to the different azimuths: 7 records with a 16-minute cadence, 0730–0906 UT.

sible to directly observe either the jet itself or its accompanying events, such as radio bursts or microflares that occurred at the time of jet initiation (Kundu et al., 1999; Nakajima and Yokoyama, 2002; Raouafi et al., 2016; Fedotova et al. 2018; Glesener and Fleishman, 2018). The combination of two-dimensional radio images at several frequencies (NoRH, SRH) and one-dimensional scans with high sensitivity and spectral resolution in a broad frequency band (RATAN-600) allows us to obtain the most complete information about the microwave radiation of the AR where the coronal jet was observed.

2.3 Detailing and Visualizing Jets on SDO/AIA Data

To obtain detailed information about jets, we used sequences of EUV images with a pixel size of 0.6″ and a 12-second cadence, obtained by the AIA instrument

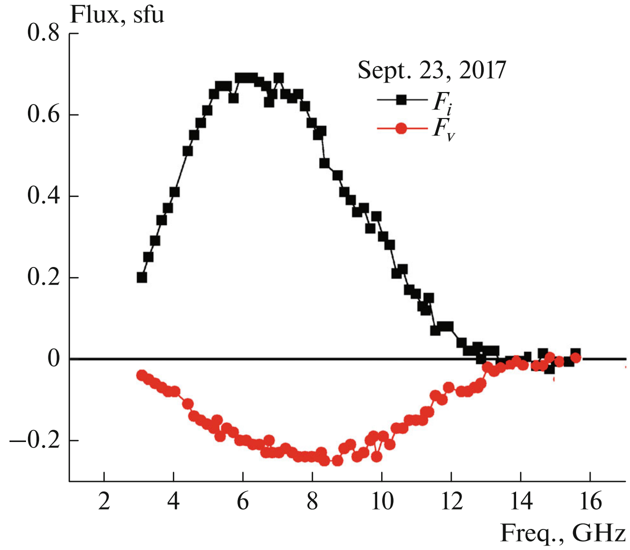

Fig. 5. Flux density spectra (I—intensity, V—polarization) from the AR 12681, observed on September 23, 2017 by RATAN-600 (0909:30 UT).

of the SDO mission (Pesnell, 2012). An original method was developed to distinguish jets, and automatically determine their parameters. The IDL code implementing the presented method is placed at https://github.com/coronal-jets (Stupishin et al., 2020). The method is based on the search for contrasting details in "running difference" images (the difference in intensity at consecutive instants of time). As a result, a report is generated containing a list of found events with their characteristics. For each event, a visualization of the dynamics seen in AIA data is provided in different spectral lines (in the form of video files in "mp4" format and as separate frames in "png" format), including the full intensity and the running difference of successive images, with a visual selection of the found jets (an example of the frame is shown in Figs. 1 and 6).

The method is applied to a number of events, mainly those that coincide in time with the observations of the RATAN-600 or the Nobeyama Radioheliograph. The results (parameter lists and visualization) are available in the catalogue. In the future, all events in the catalogue will be complemented with the information obtained by the presented method. Note that the method is implemented as an independent product and can be applied to any region of the solar disk and time interval.

2.4. Magnetic Field Data Reconstructed Into the Corona

For some events from the catalogue, images of jet events are superimposed on the photospheric magnetic field according to the SDO/HMI data (Fig. 7). However, jets are a three-dimensional phenomena, and to study their physics it is important to know the conditions above the photosphere (in the chromosphere and corona). In particular, the structure of magnetic field in the region of the Sun's atmosphere where a jet originates and propagates is of special interest.

To estimate the magnetic field above active regions a method of reconstruction (extrapolation) of magnetic field from photospheric magnetograms in the potential and nonlinear force-free approximations is widely used. The approach of the potential field corresponds to magnetic field in vacuum and assumes absence of currents and any forces. Despite its roughness, this approach describes the structure and connectivity of the magnetic field in the solar corona in the zero approximation, and also determines the configuration of the magnetic field with the lowest possible energy. The nonlinear force-free field (NLFFF)

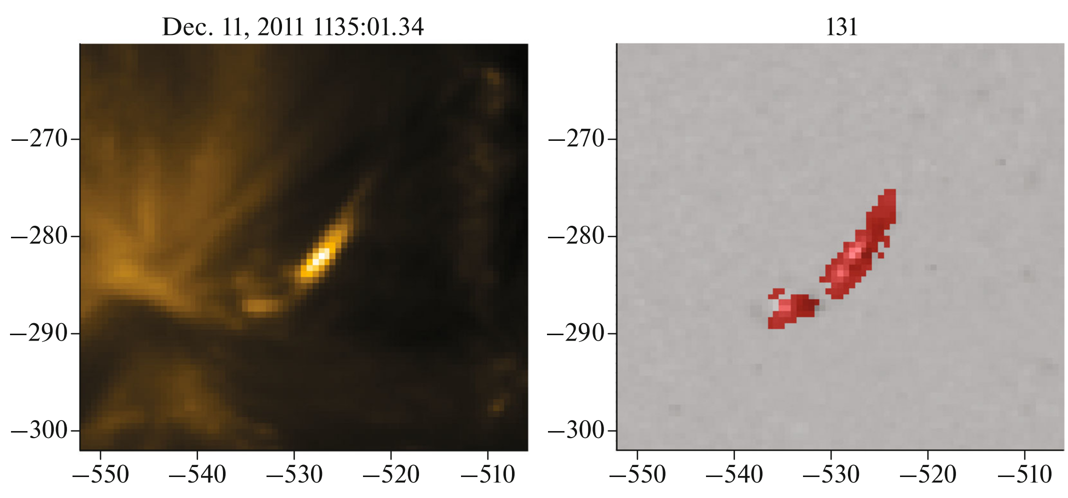

Fig. 6. An illustratory frame from the jet visualization movie (SDO/AIA 171 Å, September 11, 2011, 1135 UT). Axes are in arcseconds. Left panel: intensity, right panel: running difference. Red points mark the detected jet.

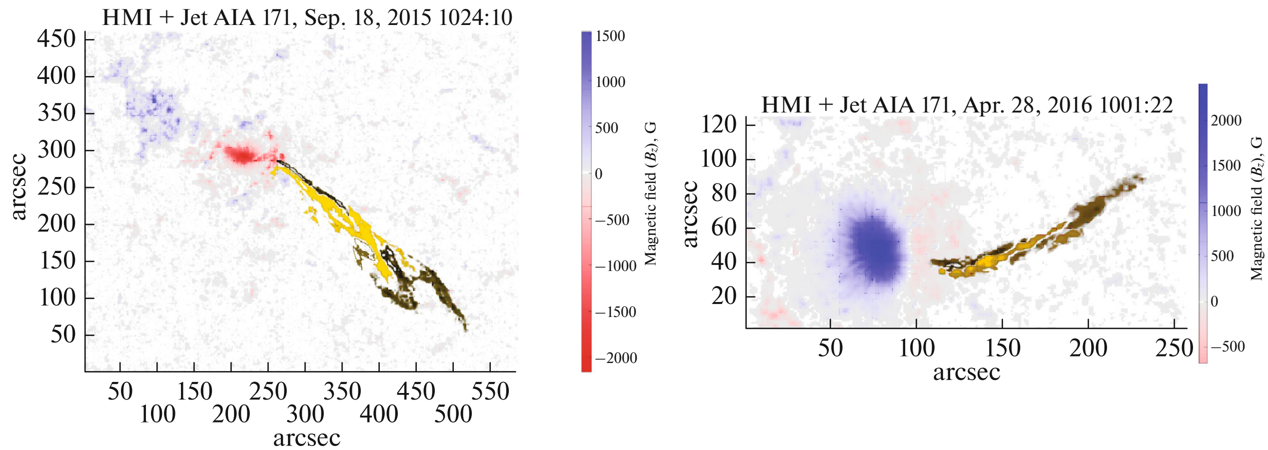

Fig. 7. Schematic structure of the detected jets over the photospheric magnetic field from September 18, 2015, 1024:10 UT (left); April 28, 2016, 1001:22 UT (right).

approach corresponds to a stationary magnetic field configuration, in which all acting forces except the magnetic one are zero, and electric currents are flows along magnetic field. This approach describes well plasma of the coronal part of slowly evolving solar active regions, where magnetic pressure prevails over the pressure of thermal plasma. Most recent methods of reconstructing magnetic field in the corona from photospheric magnetograms work in the NLFFF approach. Currently, the most commonly used optimization method is NLFFF extrapolation based on (Wheatland et al., 2000), which was subsequently significantly developed in a number of other works (primarily in (Wiegelmann, 2004)).

If a jet-like event occurs in an active region observed on the Sun's disk not close to the limb, it is possible to perform such a magnetic field reconstruction from photospheric observations and evaluate the relationship between the field topology and the derived jet parameters. The catalogue contains the NLFFF-reconstructed magnetic field data for a number of events, based on the original implementation of the method proposed in (Wiegelmann, 2004), and developed and tested by us in (Fleishman et al., 2017). The current version of the code in the IDL language is presented in (Stupishin, 2020). The field reconstruction results for specific time instants (with the active region number, time, and Carrington coordinates specified in the file name) are presented in the IDL-readable "sav" file format and are ready for use in the GX-simulator package (Nita et al., 2015). An example of the reconstructed field is shown in Fig. 8.

3. DISCUSSION

The processes responsible for formation and evolution of hot plasma jets observed in the solar corona remain poorly understood. The main questions are related to the mechanisms for the acceleration and collimation of the plasma. In the first case, we are interested where the forces accelerating the jet are localized in time and space. In other words, whether the flow is "ballistic" or of the type of a free fall, when the main movement of the plasma is carried out after the "engine shutdown" and is determined by the forces of gravity and, possibly, some form of friction, or "reactive", when the accelerating forces act for the entire or almost the entire lifetime of the jet stream. Is the acceleration mechanism associated with magnetic reconnection, in particular, is the observed jet an Alfven flow in the Sweet–Parker model? What is the direction of the magnetic field in the jet plasma, along or across it? In other words, whether a given magnetic field has an accelerating or decelerating effect, and whether it is related to the magnetic tension force, as in the case of a transverse field, or to the magnetic pressure gradient, as it could be in the case of a longitudinal field. Another acceleration mechanism may be a siphon mechanism associated with the gradient of gas or total pressure along the jet and parallel to its axis of the field. The mechanisms for jets, which counteract its expansion and filamentation in the transverse direction, can also be associated with the magnetic field, for example, with its helical geometry. Of particular interest are macroscopic plasma instabilities, such as the Kelvin–Helmholtz instabilities (Zaqarashvili et al., 2015) and negative-energy waves (Yu and Nakariakov, 2020). The answers to these questions require a developed theory of jet flows in plasma with magnetic field and their stability, but its comparison with the observational data and validation are possible only when comparing the relationship of the observed and theoretically predicted parameters of jets (determining their scaling).

The developed catalogue creates a reliable observational base for searching for statistical patterns in the ensemble of the observed jets and in the active regions where they occur. In particular, it allows us to deter-

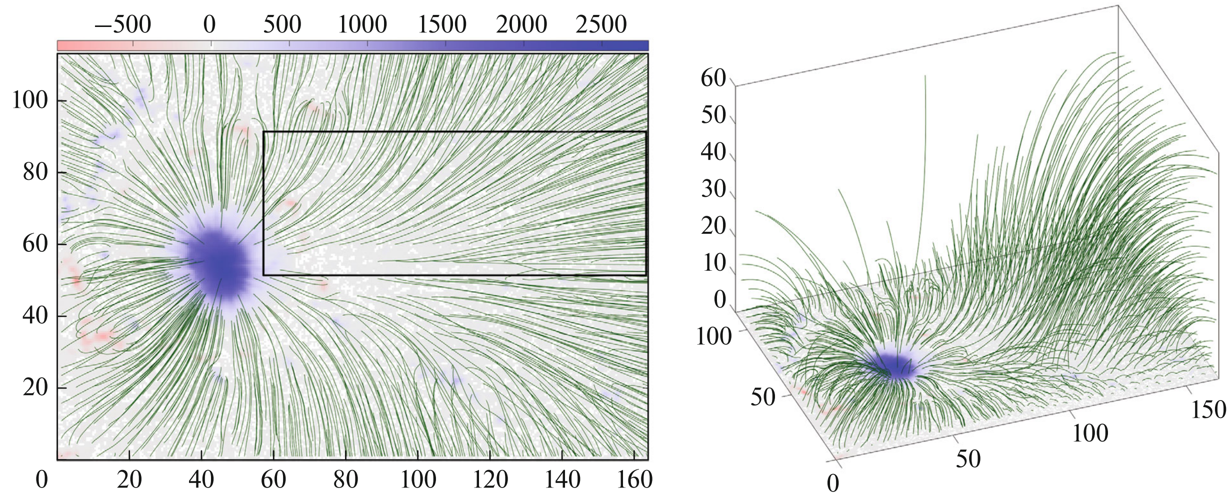

Fig. 8. Top and side views of the reconstructed magnetic field lines for the AR 12533 (April 28, 2016). Axes are in arcseconds. The black rectangle outlines the estimated region of the jet registration.

mine distributions of the jet parameters and their possible anomalies, empirical dependencies of their lifetimes, velocities and accelerations, with the plasma parameters inside and outside jets. The derived jet distribution features are to be used for the first empirical classification of hot jets, which may be associated with the generation of jets by various mechanisms. Obtaining statistical data on the angles of inclination of the jet axes relative to the Sun's surface and their evolution during the solar cycle will significantly improve the determination of the global geometry of the magnetic field using the method proposed in (Nisticò et al., 2015).

The shape of a jet and the evolution of its cross-section are of special interest. The geometry of active regions can provide important indications of the possibility of magnetic reconnection in the jet initiation region. Independent information about the energy release due to reconnection and its intensity at different phases of jet evolution comes from observations of non-thermal radiation, in radio in particular. The statistical relationship of the jet parameters with the probability of wave and oscillatory processes observed in them will allow us to determine the conditions for the occurrence of these dynamic phenomena and optimize their search. Studying properties of the longest jet-like features (or features with the smallest diameter-to-length ratio) will contribute into evaluation of the optimal conditions for their collimation and macroscopic stability. The information obtained will be of interest not only for solar physics, but also for the other fields of astrophysics and physics, for example, for the analysis of astrophysical and magnetospheric jets and for the study of artificially created plasma.

4. CONCLUSIONS

A multi-wavelength catalogue of plasma jets with temperatures above 0.5 MK ("hot jets") in the Sun's corona has been created. To the moment, the catalogue is based on the data for the period of 2010–2018, which almost completely covers the 24th cycle of solar activity. The catalogue includes: primary information about the event, observed jet parameters, and associated eruptive phenomena. The catalogue contains data obtained with the SDO/AIA high-precision EUV telescope, the results of extrapolation of magnetic fields based on photospheric observations of the magnetic field using the SDO/HMI instrument, and the data from the ground-based radio telescopes and spectrometers, including RATAN-600, SRH, and NoRH. The catalogue is implemented on an online platform that provides open access. The catalogue includes the possibility of direct access to video information based on the visualization of three-dimensional data cubes of imaging telescopes (two spatial coordinates in the plane of the sky and time) and time-distance maps built on several spatial slices (slits), as well as adding calculated parameters, including the results of extrapolation of photospheric magnetic sources and, in the future, the results of magnetohydrodynamic seismology. It is planned to continue filling the catalogue with data, including information about the X-ray radiation accompanying the jets.

The purpose of the catalogue is to determine the physical mechanisms responsible for the generation, collimation, and dynamics of plasma jets in the solar atmosphere by combining data analysis with numerical modeling of MHD processes. Further objectives include the analysis of the correspondence of magnetic configurations to existing models of MHD jet generation, calculations of their EUV, radio and X-ray radiation; analysis of dynamic processes, such as accompanying oscillating processes and instabilities. Of particular importance is the possibility to compare simultaneous observations of thermal and non-thermal radiation.

The catalogue will allow searching for statistical patterns, such as mutual dependencies between different observed parameters. Comparisons of the observed statistical patterns with the dependencies predicted by various models will help to make a choice in favor of one or another mechanism for jet formation and evolution.

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CONFLICT OF INTEREST

The authors state that they have no conflict of interest.

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