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Advances in Space Research 47 (2011) 1538–1543

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Results of solar observations by the CORONAS-F payload

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Received 4 October 2010; received in revised form 17 December 2010; accepted 20 December 2010
Available online 7 January 2011

Abstract

The CORONAS-F mission experiments and results have been reviewed. The observations with the DIFOS multi-channel photometer in a broad spectral range from 350 to 1500 nm have revealed the dependence of the relative amplitudes of p-modes of the global solar oscillations on the wavelength that agrees perfectly well with the earlier data obtained in a narrower spectral ranges. The SPIRIT EUV observations have enabled the study of various manifestations of solar activity and high-temperature events on the Sun. The data from the X-ray spectrometer RESIK, gamma spectrometer HELICON, flare spectrometer IRIS, amplitude–temporal spectrometer AVS-F, and X-ray spectrometer RPS-1 have been used to analyze the X- and gamma-ray emission from solar flares and for diagnostics of the flaring plasma. The absolute and relative content of various elements (such as potassium, argon, and sulfur) of solar plasma in flares has been determined for the first time with the X-ray spectrometer RESIK. The Solar Cosmic Ray Complex monitored the solar flare effects in the Earth's environment. The UV emission variations recorded during solar flares in the vicinity of the 120-nm wavelength have been analyzed and the amplitude of relative variations has been determined.

Keywords: Solar activity; Solar emissions

1. Introduction

The joint Russian–Ukrainian satellite CORONAS-F (the name KORONAS-F was also used for this mission) observed solar activity and studied solar–terrestrial coupling (was launched July 31, 2001; end of the mission December 6, 2005). The satellite was orbiting the Earth at a height of about 500 km; the orbit inclination was 83°. The scientific payload of the satellite comprised 15 instruments, which enabled observations of the Sun in the entire electromagnetic spectrum from optical radiation to gamma rays. During the decline phase of 23rd solar cycle the satellite observed the major solar flares and their effects on the Earth's space environment.

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0273-1177/$36.00
doi:10.1016/j.asr.2010.12.020

2. SPIRIT experiment

During the SPIRIT experiment (Zhitnik et al., 2002) more than 10000 XUV (8-350 A) observation sessions were carried out, both autonomic and synchronized with other space (SOHO, TRACE) and ground-based observations with radio and optical telescopes. A vast observational database has been formed, which comprises more than 500 million solar images, including those in monochromatic lines.

Synchronous observations in different "monotemperature" SPIRIT telescope channels have revealed a complicated temperature and height structure of plasma features in the solar corona. In particular, coronal mass ejections at velocities up to hundreds of km/s (Zhitnik et al., 2003a) and the accompanying phenomena (dimmings, transient coronal holes, and coronal waves) have been detected in different spectral lines. They are indicative of complicated interaction of "cold" and "hot" coronal plasmas. The SPIRIT data have been used together with the data from BST-1 (CrAO, Ukraine) to study the height structure of coronal holes. It is shown that there are both coronal holes contracting and expanding with height. The remote solar corona (up to 4 solar radii) has been studied with unique instruments – XUV coronograph and XUV spectroheliometer. Different variation of the emission of "cold" plasma in the HeII line (0.05–0.1 MK) and coronal plasma in the FeIX-XIII, SiX lines has been demonstrated (Zhitnik et al., 2003b).

A catalog of the spectral lines in the solar corona in the ranges of 176–206 and 279–335 A has been compiled. The catalog comprises more than 170 lines. The lines corresponding to the ions with equal degree of ionization have been selected for diagnostics of plasma parameters of various coronal features. It is shown that, in the flares recorded, N_e was $5–10 \times 10^9$. The differential measure of emission for different coronal features has been determined by the density-independent lines.

The channel for monochromatic imaging in MgXII (8.42 A) characterizing plasma with a temperature $T_e \approx 10^7$ K proved to be most informative. It provides a highly variable pattern of plasma features with different lifetimes (from minutes to tens of hours), shapes, and height distribution over the solar disk (up to hundreds of thousands of km) (Fig. 1) (Zhitnik et al., 2003c). It turns out that such high-temperature plasma exists virtually permanently in the solar corona. The active regions observed in this line are characterized by intensity oscillations with the periods from minutes to hours. The dynamic characteristics of the flares recorded in the channel under discussion have been investigated (Bogachev et al., 2010). Multi-spectral observations in a broad energy range have been used to measure the density of over-limb hot features observed in this line and to study their relation to the coronal magnetic fields.

More detail review of SPIRIT results can be found in (Zhitnik et al., 2005).

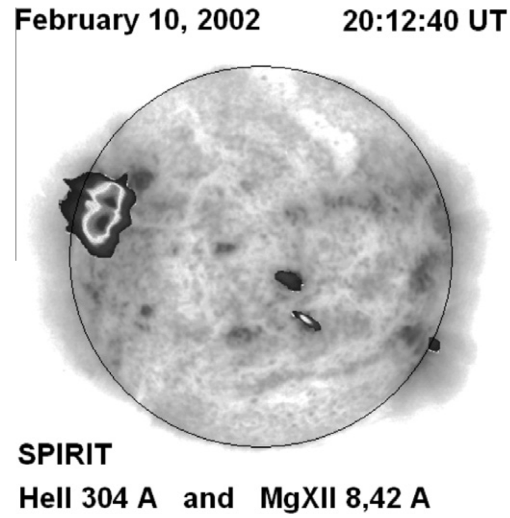

Fig. 1. The SPIRIT superposed images of the Sun in HeII 304 Å and MgXII 8,42 Å lines.

3. Solar flares

A number of the CORONAS-F instruments are designed to measure the Solar Flare Emission in a broad energy range with a high temporal and spectral resolution. These instruments have provided new experimental data on the physical processes in solar flares, such as build-up and release of the magnetic energy, energy spectra, nuclear lines, gamma-radiation time profiles, X-ray dynamic spectra, profiles of various spectral lines of the flare plasma, polarization of the flare-generated X-rays, etc.

3.1. X-ray spectrometer RPS-1

The sensitive X-ray spectrometer RPS-1 (Pankov et al., 2006) recorded pre-flare enhancements and minor X-ray flares (importance C and M) in the energy range of 3–30 keV. The dependence of the X-ray background spectrum on solar activity (sunspot number) has been studied in the absence of flares (in the period of October 2003 characterized by dramatic variation of the solar activity level). At the sunspot minimum, the spectrum was soft and did not exceed 6–7 keV. At the sunspot maximum, the spectrum was hard and reached 20 keV, which was due to the appearance of very hot regions (AR 484 and AR 486) (Fig. 2).

These spectra give an idea of pre-flare heating and can be used to improve the forecast of solar flares.

3.2. Flare spectrometer IRIS

The flare spectrometer IRIS measures the flare-generated X-rays (2–200 keV) with a high time resolution (10 ms) simultaneously in four energy channels. The most direct evidence of magnetic reconnection processes in solar flares is a fast time structure of hard X-rays. Sub-second pulses detected in nonthermal hard X-rays are generally

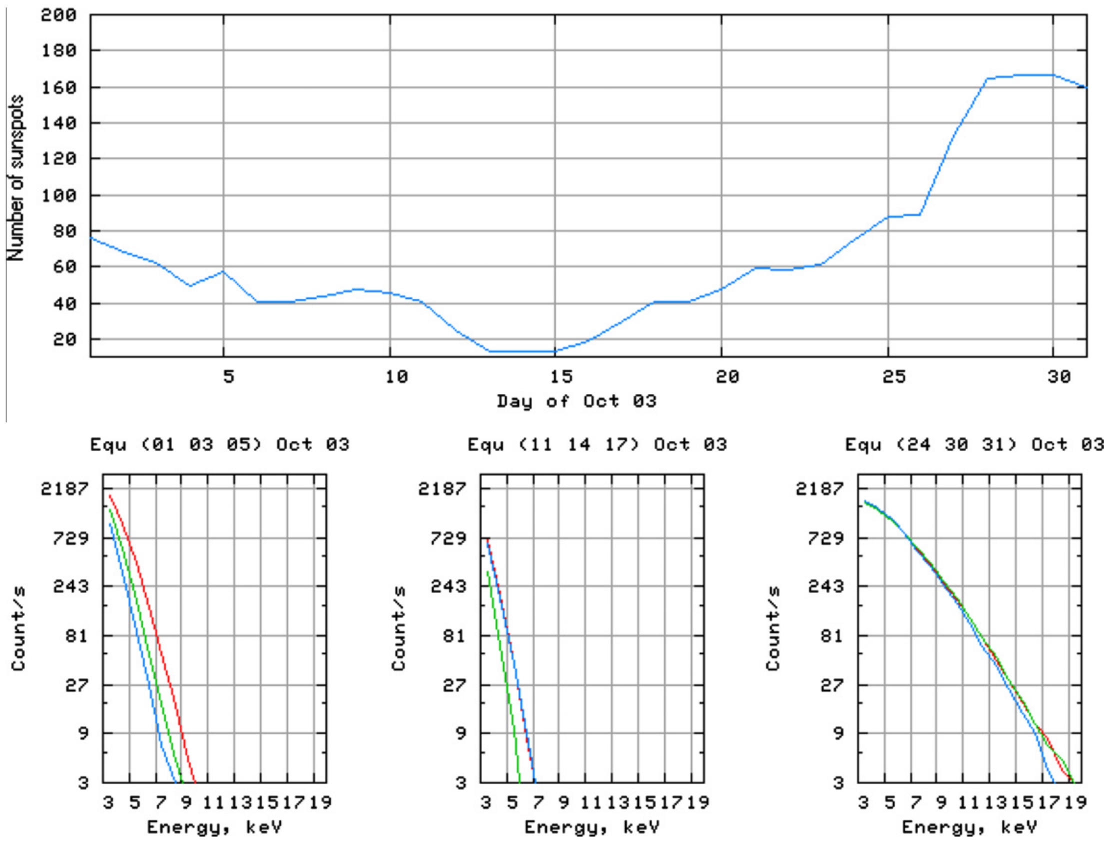

Fig. 2. Background spectra dependence on a level of the solar activity (Kuznetsov et al., 2004).

interpreted as bremsstrahlung from electrons accelerated in the lower corona. The time profiles of the hard X-rays detected in the solar flare of August 20, 2002 displayed an outstanding feature of this flare – a fast burst with duration of 80 ms and FWHM about 30 ms detected at 28:16.77 UT (Fig. 3). The confidence level of this peak is 6σ and the time profile includes eight time points following each other at 10.4 ms intervals. These facts exclude accidental nature of this pulse. The same time structure was not observed in the rise and peak phases of the flare.

3.3. DIAGENESS spectrophotometer and X-ray spectrometer RESIK

DIAGENESS spectrophotometer and X-ray spectrometer RESIK operating in the 3–7 A X-ray spectral range have detected multiple spectral lines in the emission of the most intensive solar flares ever observed. DIAGENESS spectrophotometer has observed for the first time the evolution of spectra in vicinity of He-like ions of Si XIII, S XV and Ca XIX He-like ions with high resolution. This has been possible for the entire duration of the X5.3 class flare of 25 August 2001. Thanks of a special arrangement of the scanning crystals in so-called X-ray Dopplerometer configuration, absolute blue-shifts of entire emission lines have been observed allowing for estimates of absolute value of the hot plasma radial velocity component (Fig. 4).

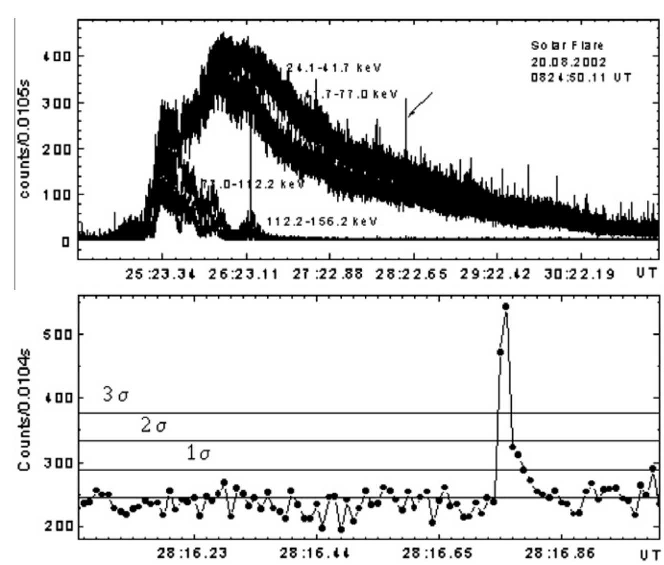

Fig. 3. The time profiles of hard X-rays detected in solar flare of August 20, 2002 (Kuznetsov et al., 2004).

X-ray spectrometer RESIK has measured hundreds of thousands of spectra in the unexplored range between 3.3 A and 6.1 A. Tens of new spectral lines has been identified by investigating the variations of spectral shapes emitted by plasma of different temperature (Sylwester et al., 2005).

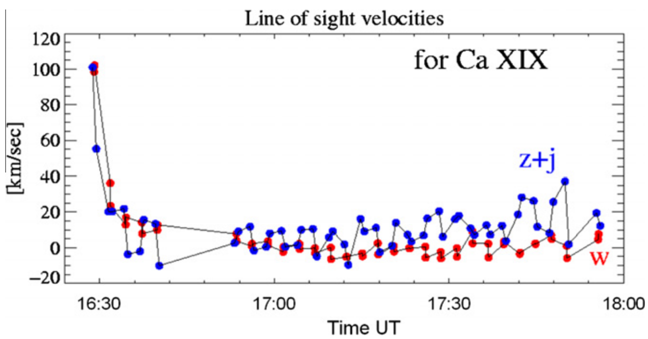

Fig. 4. First measurements of absolute Doppler shifts for X-ray lines formed in hot multimillion degrees solar flare plasmas – detection of fast plasma motions during early phase of 25 August 2001 X5.3 flare (Plocieniak et al., 2002).

Thanks to the high sensitivity of the instrument, week lines from K and Cl have been observed and absolute abundances of these elements in the corona have been determined for the first time (Sylwester et al., 2008, 2010a, 2010b).

3.4. Solar X-ray spectropolarimeter SPR-N

The solar X-ray spectropolarimeter SPR-N is measuring polarization of the solar-flare hard X-rays in the range of 20–100 keV, which occurs as high-energy electron beams interact with the dense solar atmosphere. A large polarization was observed during the bursts of emission associated with the flare of October 20, 2003 (Zhitnik et al., 2006), the harder radiation being stronger polarized. Then, a smooth transition to the background values took place by the end of the flare. At the beginning of the flare the polarization was 50–60% in the 20–40 keV channel and 70–100% in the 40–60 keV and 60–100 keV channels. Then, the polarization in the 20–40 keV channel was decreasing monotonically over the entire time profile of the flare. In the 40–60 keV and 60–100 keV channels, the degree of polarization was the greatest at the peaks of the flare intensity. In the flare of October 29, 2003, the polarization was in east–west direction.

3.5. Gamma spectrometer HELICON

The gamma spectrometer HELICON is measuring the flare-generated hard X-ray and gamma radiation with a high temporal and spectral resolution in eight energy channels. On the basis of these measurements, the dynamics of the hard radiation spectrum has been studied in all phases of the flare, including the characteristic values and timescales of variations in the spectrum inclination (Fig. 5).

3.6. AVS-F device (amplitude-temporal spectrometry)

More than 30 solar flares of class M2 and higher in GOES classification were recorded during 2.5 years of AVS-F device operation in the energy range $E_\gamma \geqslant 50$ keV.

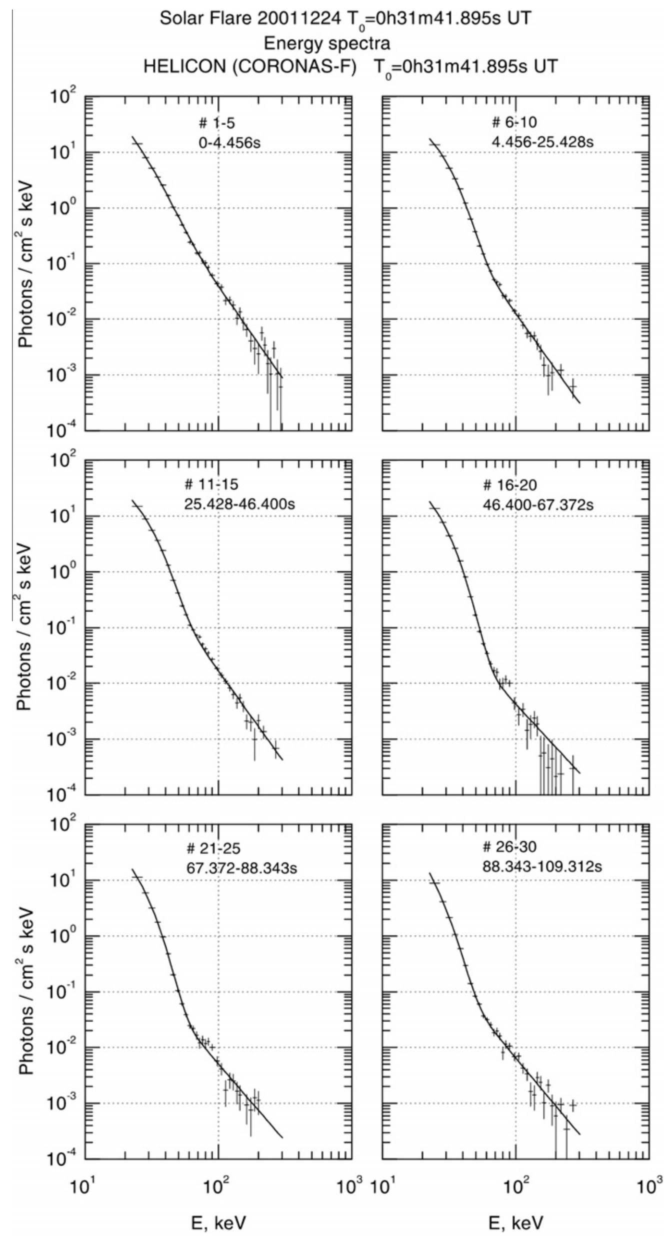

Fig. 5. Energy spectra of the major flare of December 24, 2001, obtained in succession for different phases of the event (0–109 s) (Kuznetsov et al., 2004).

As it is well known, 30 active regions were present on the Sun during October–November 2003 according to SOHO data. Four regions (0484, 0486, 0488, 0490) produced hard X-ray and gamma-ray emission.14 flares of class M and X were detected during this time by GOES, HESSI and other experiments. Five solar flares were detected by AVS-F instrument at that time. One of the most intense events was observed on October 29 from 20:37 to 21:01 UT by the devices onboard GOES-12 (class X10, ball 2B, NOAA region 0486, S15W02). This flare was observed by AVS-F instrument at 20:39:00–20:58:00 UT as the satellite was passing through the equatorial zone (Fig. 6). Six gamma-line complexes were observed in the energy spectrum of this

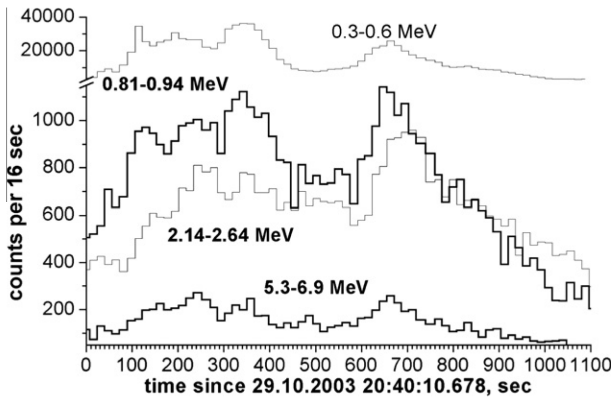

Fig. 6. Light curves of the flare 29.10.2003 registered by AVS-F in the energy bands 0.3–0.6 MeV, 0.81–0.94 MeV, 2.14–2.64 MeV and 5.3–6.9 MeV (Kuznetsov et al., 2004).

flare: 0.81–0.94, 1.51–1.74, 2.9–3.4, 4.0–5.0 and 5.3–6.9 MeV corresponding to ^{56}Fe, $^{24}Mg+^{20}Ne+^{28}Si$, $^{20}Ne+^{16}O$, ^{12}C and ^{16}O lines, respectively. These lines and the line from the neutron capture at 2.2 MeV were seen during ~20 min. The temporal profiles of the radiation in the energy ranges corresponding to prompt gamma-lines differ from that in the neutron capture line. Several temporal maxima were observed in all mentioned energy ranges. The maximum of emissivity in the gamma-lines does not coincide with the soft X-ray maximum observed at 20:49:00 by GOES-12. But one of the gamma-line emission maxima at 20:48 (in the energy ranges 0.81–0.94 MeV, 2.14–2.64 MeV, 4.0–5.0 MeV and 5.3–6.9 MeV) coincides with the maximum detected in 12–25 keV by RHESSI.

4. Solar Cosmic Ray (SCR)

Measuring Solar Cosmic Rays along its orbit with the SCR Complex (Gamma Emission Spectrometer SONG, Cosmic Ray Monitor MKL, Cosmic Emission Spectrometer SKI-3), CORONAS-F performs monitoring of radiation conditions in the near-Earth space and dynamics of the Earth's magnetosphere and radiation belts during active events in the Sun. The data obtained are used to study solar flares, geomagnetic storms, penetration of energetic particles into the Earth's magnetosphere, and strong deformations of the magnetosphere and radiation belts. Quasi-periodic pulsations (QPP) of gamma-ray emission with a period of about 40 s are found in a single loop X-class solar flare on 2005 January 1 at photon energies up to 2–6 MeV with the SONG (Nakariakov et al., 2010). It is established that only 20% of the recorded flares have caused geomagnetic storms. One third of the flares were accompanied by the appearance of Solar Cosmic Rays at the Earth's orbit. Gamma rays with the energy up to 100 MeV and neutrons with the energy of hundreds of MeV were recorded simultaneously during the flare of August 25, 2001.

5. Solar UV radiometer SUFR-Sp-K and solar UV spectrophotometer VUSS-L

A large volume of data on the solar UV fluxes, which affect the Earth's upper atmosphere and serve as an important characteristic of solar activity during a cycle, have been obtained with the solar UV radiometer SUFR-Sp-K and solar UV spectrophotometer VUSS-L (Nusinov et al., 2005, 2006). It is found out that, even in the major flares, the increase of UV radiation at 120 nm does not exceed a few percent. The correlation between the solar UV and radio fluxes has been determined for different observations periods. It is used to estimate the UV radiation and monitor the Earth's atmospheric conditions in the periods when the satellite UV data are absent and the ground-based radio flux measurements alone are available.

6. DIFOS spectrophotometer

Global oscillations of the Sun have been observed with the DIFOS spectrophotometer in a broad wavelength range of 350–1500 nm, and new experimental data on their manifestations in the observed radiation have been obtained, namely a significant growth of the oscillation amplitude in the UV spectral range. It is established that the amplitude depends on the wavelength (approximated as $\lambda^{-1.2}$) that agrees fairly well with earlier observations in separated more narrow spectral ranges (Lebedev et al., 2004).

7. Conclusion

For the entire period of operation, the satellite has provided more than 500 thousand high-resolution X-ray images of the Sun, numerous time profiles of the solar flare radiation in a broad energy range, new data on the Solar Cosmic Ray and UV fluxes. More detail results of CORONAS-F mission can be found in (Kuznetsov, 2009).

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