Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 58 (2016) 635–643

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Solar X-ray polarimetry and spectrometry instrument PING-M for the Interhelioprobe mission

Yu.D. Kotov [a], V.N. Yurov [a], A.S. Glyanenko [a], E.E. Lupar [a], A.V. Kochemasov [a], Yu.A. Trofimov [a,*], M.S. Zakharov [a], R.M. Faradzhaev [a], V.G. Tyshkevich [a], I.V. Rubtsov [a], V.A. Dergachev [b], E.M. Kruglov [b], V.P. Lazutkov [b], M.I. Savchenko [b], D.V. Skorodumov [b]

[a] *National Research Nuclear University MEPHI, Moscow, Russia*
[b] *Ioffe Institute, St. Petersburg, Russia*

Received 27 October 2015; received in revised form 2 April 2016; accepted 13 May 2016

Abstract

The PING-M experiment is designed to investigate solar X-ray activity. The instrument includes a hard X-ray polarimeter (PING-P), a hard X-ray spectrometer (HXRS) and a soft X-ray spectrometer (SXRS). PING-P has the energy range of 20–150 keV and an effective area of about 2.5 cm^2. It uses three organic scintillation detectors as active scatterers, which work in coincidence with six absorber detectors, based on CsI(Tl) scintillator. This technique allows us to considerably improve the polarimeter sensitivity. HXRS has the energy range of 20–600 keV and an effective area of about 15 cm^2. It is based on a fast inorganic scintillator ($LaBr_3$(Ce) or $CeBr_3$) with a relatively high energy resolution of 3.5–4.5% at 662 keV. The SXRS energy range is 1.5–25 keV, and its aperture is ø0.1 mm, which provides the registration of solar flares in the range from C1 to X20 class of GOES scale. It is based on a SDD semiconductor detector with an energy resolution better than 200 eV at 5.9 keV line. The experiment will be performed onboard the Russian interplanetary mission Interhelioprobe which is planned for launch after 2025.

The instrument will allow us to investigate angular and energy distributions of accelerated electrons, plasma heating processes, etc. Stereoscopic polarimetry and spectrometric observations will be possible if a similar instrument is installed onboard a near Earth satellite, or the second probe of the Interhelioprobe mission.

Keywords: PING-M; Solar flares; Solar X-ray and gamma-ray spectrometry; Solar X-ray polarimetry; $CeBr_3$ intrinsic activity; Cosmic gamma-ray background

---

1. Introduction

Solar X-ray emission measurement is the most valuable diagnostic tool for investigation of plasma heating and particle acceleration processes that occur during solar flares.

The accelerated electrons that propagate along the magnetic loop interact with ambient plasma and generate bremsstrahlung X-ray, which dominates in solar flare spectra in the energy range over a few tens of keV. Hard X-ray observational data (so-called non-thermal emission of the flare) can be used for a reconstruction of electron flux spectra, e.g. via forward fitting or regularized inversion methods (Kontar et al., 2011). However, downward emitted photons, which are backscattered by the photosphere (albedo photons), contaminate the observed bremsstrahlung spectrum and lead to wrong estimation of electron spectral parameters. High resolution spectral observational

---

* Corresponding author. Tel.: +7 9265260192.
E-mail address: YuTrofimov@gmail.com (Y.A. Trofimov).

http://dx.doi.org/10.1016/j.asr.2016.05.024
0273-1177/

data are necessary to separate the albedo contribution from flare spectra (Kontar et al., 2006a).

The measured hard X-ray spectra strongly depend on the angular distribution of electrons and the observation angle (the angle between the observer direction and the electron beam propagation direction). There are several spectrometric approaches to study the electron beams anisotropy: a statistical analysis of the dependence of X-ray spectrum hardness on the observation angle (or the flare position on the solar disc), simultaneous measurement of solar flares from different directions (stereoscopic technique) and the discrimination of direct and backscattered bremsstrahlung X-ray ("Compton mirror" technique). The statistical approach shows a clear center-to-limb variation of the spectral parameters, e.g. Bogovalov et al. (1997), Kasparova et al. (2007), while the stereoscopic technique suffers from cross-calibration issues between different instruments and doesn't show a clear correlation (Kane et al., 1998). The "Compton mirror" technique showed near-isotropic electron distributions for at least two flares, which contradicts the standard solar flare model (Kontar and Brown, 2006b).

Theoretical models show that X-ray emission generated by an anisotropic electron beam is polarized. The polarization degree may vary from a few per cent up to 60% depending on the angular and energy distribution of accelerated electrons and the observation angle (Bogovalov et al., 1988). The plane of X-ray polarization contains the electron propagation direction and the observation direction. The polarization degree of emission generated by electrons with isotropic angular distribution is much less (<5%) and it does not strongly depend on the energy distribution of electrons and the observation angle (Bai and Ramaty, 1978). For these reasons, polarization measurements of solar flares can be used as a method of electron anisotropy detection. The total polarization degree depends on the energy distribution of bremsstrahlung X-ray and may include backscattered X-ray polarization (Jeffrey and Kontar, 2011). Therefore simultaneous precision spectrometric measurement is necessary to make the interpretation of measured data more reliable.

Since 2000 only three space instruments have measured the polarization of solar hard X-ray emission. The SPR-N/CORONAS-F instrument measured the polarization of 25 flares in the energy range 20–100 keV. This instrument showed a very high polarization degree (50–70%) for the flare that occurred on 29 October 2003 (Zhitnik et al., 2006). As the flare occurred near the center of the solar disk, this result contradicts the theoretical models. Such a result can be explained if we make the assumption that there is an abnormal tilt of the magnetic loop plane relative to the solar surface. Another experiment is RHESSI, which was designed primarily as an instrument for solar imaging spectrometry in the energy range from 3 keV to a few MeV with a high spatial and spectral resolution (Lin et al., 2002). It can also measure solar X-ray polarization in the energy range from 20 keV to 1 MeV. Since the RHESSI design is not optimized for polarization measurements, the statistical significance of the measured polarization is limited. For example, Suarez-Garcia et al. (2006) obtained the polarization degree between 2% and 54% with the errors ranging from 10% to 26%. The third instrument PINGUIN-M/CORONAS-PHOTON did not measure statistically significant events due to the low level of solar activity during the mission (Kotov et al., 2011).

Statistical accuracy of most measurements is insufficient because of the low sensitivity of the instruments and high background count rates. Also, all collected data cannot be described by the common flare loop model (Kotov, 2010). New high quality polarization measurements would be useful for more detailed investigation of the electron acceleration process and for the improvement of the theoretical models of the solar flare.

Plasma heating is another process, which consumes the energy released in solar flares. Plasma heated to the temperature of about 10MK generates thermal soft X-ray emission. The main parameters of such plasma are temperature and emission measure. It was shown that these parameters can be obtained by means of the data of two broadband channels of the XRS/GOES sensors: 0.5–4 and 1–8 Å, or about 3.1–24.8 and 1.55–12.4 keV respectively (White et al., 2005). But this technique is correct only in the model of isothermal plasma. However, the RHESSI high-resolution spectral measurements in the 1 – 20 keV energy range provided the evidence of the multi-temperature nature of plasma emission, (e.g., Aschwanden, 2008a; Caspi et al., 2014).

Temperature of the solar corona is one of its most fundamental characteristics. It affects the nature of a number of physical processes and plasma properties such as radiation, conduction, waves, shocks, the plasma-β, hydrodynamics, etc. The observational studies of flare thermal energy budgets (e.g., Emslie et al., 2012), thermodynamic properties (e.g., Feldman et al., 1996; Ryan et al., 2012), hydrodynamic scaling laws (e.g., Rosner et al., 1978; Aschwanden et al., 2008b), flare cooling (e.g., Raftery et al., 2009; Ryan et al., 2013), as well as many others, all depend on the temperature measurements.

There is another approach to diagnose heated plasma: 6.7 keV Fe and 8.0 keV Fe/Ni lines, which can be observed when the temperature of plasma exceeds 10MK. The theoretical model shows that the mean energy and width of these lines depend on the plasma temperature (Phillips, 2004). The RHESSI data analysis generally confirms the theoretical prediction (Phillips et al., 2006), but the instrumental energy resolution at these energies (1 keV FWHM) is not sufficient. On the other hand, bent crystal spectrometers, which are typically used for soft X-ray lines observations (like RESIK/CORONAS-F (Sylwester et al., 2005), have much better energy resolution (about a few eV) but narrow energy ranges. For this reason, such spectrometers do not provide the possibility of plasma temperature measurement by means of thermal spectrum analysis. A broad energy range soft X-ray spectrometer, with a energy