The X-ray polarimeter of solar flares for the Interhelioprobe mission: experimental determination of the response of the physical model to polarized x-ray radiation

M I Savchenko\textsuperscript{1}, E M Kruglov\textsuperscript{1,2}, V P Lazutkov\textsuperscript{1}, D V Skorodumov\textsuperscript{1} and I I Shishov\textsuperscript{1}

\textsuperscript{1}Ioffe Institute, 26 Politekhnicheskaya st., St. Petersburg 194021, Russian Federation
\textsuperscript{2}V.G. Khlopin Radium Institute, 28 Second Murinsky Ave., St. Petersburg 194021, Russian Federation

E-mail: Mikhail.Savchenko@mail.ioffe.ru

Abstract. The work is devoted to the study of the characteristics of the PING-M hard x-ray polarimeter using its physical model (PING-P FM). The PING-M instrument is developed jointly by the Moscow Engineering Physical Institute and the Ioffe Institute for the mission "Interhelioprobe". The operation of the device is based on Compton scattering. The degree and direction of linear polarization are determined by measuring the asymmetry of the scattered radiation field. The device uses active scatterers that register the Compton recoil electron. A useful event is the case when two impulses in the detector-scatterer and in the detector-receiver of scattered radiation coincide. The physical model represents the detector part of the polarimeter. It contains three scatterers and six receivers of scattered radiation – a total of 18 pairs of detectors oriented at different azimuthal angles. As a result of the experiments, the dependences of counting rates in pairs of detectors on the positional angle of the polarization plane of the incident radiation were measured. The modulation depth of this dependence determines the sensitivity of the device to the polarization degree. The sensitivity of the device is estimated.

1. Introduction
The PING-M x-ray polarimeter [1] is developed for measuring the degree and positional angle of linear polarization of hard x-ray radiation from solar flares, as well as for measuring the time and energy characteristics of soft and hard x-ray radiation of active formations on the Sun. The device consists of two blocks: PING-PIRS and PING-P. The PING-P block is designed to study the polarization of hard x-ray radiation. The PING-M instrument is part of the scientific payload of the interplanetary station "Interhelioprobe" [2], aimed at observing the Sun from close heliocentric distances down to 0.3 AU.

X-ray radiation, propagating from the generation region to the observer without significant distortion, is one of the main channels for obtaining information about solar flares. Polarization, along with the spectral and temporal characteristics of hard x-ray radiation, carries information about the processes occurring in flares, the parameters of the plasma, and the spectrum of electrons accelerated during the flare. The polarization and directivity of hard x-ray radiation provides information about the anisotropy of accelerated electrons. In the absence of accelerated electron
beams, the degree of polarization of x-rays, resulting due to reflection from the solar atmosphere, cannot exceed ~ 4% [3]. Thus, the presence of a significant degree of linear polarization of radiation indicates the existence of anisotropic electron distributions [4,5].

Although the first measurement of the polarization of hard x-rays from solar flares was done in 1969 [6], the total number of polarimetric experiments is insignificant and there is still a lack of reliable data in this area. This is largely due to the technical difficulties of such experiments and high requirements for measurement accuracy. All solar x-ray polarimeters were based on measuring the asymmetry of the scattered radiation field when polarized radiation is scattered. The design of such polarimeters consists of a scatterer and surrounding detectors that register scattered radiation. Most often, solar polarimeters contained a single scatterer made of beryllium [6,7,8]. In these experiments, the problem of the identity of the measuring channels was quite pressing. To prevent appearance of a false polarization signal, which can occur due to drift of parameters of detectors, in some cases a rotating mechanism was employed or the rotation of the whole satellite was used [7,8]. In the PING-M device, a different method is proposed to mitigate the false polarization signal arising from non-identity of the measuring channels, without mechanical rotation of the device. The scattering block consists of three separate active scatterers that mark the fact of Compton scattering by registering the recoil electron. Scattered radiation is detected by six receiver detectors common to all scatterers. A useful signal is the fact that the electrical pulse from one active scatterer coincides with the pulse from one receiver detector. In fact, we have three differently oriented polarimeters using the same receiver detectors. Such a redundancy of information makes it possible to distinguish between the instrument effects and the real signal caused by the presence of polarization of the analyzed radiation.

The sensitivity of the polarimeter is determined by the effective area of the instrument and the modulation depth of the signal from polarized radiation. In our previous work [9], the degree of identity of the measuring channels was investigated and the effective area of the polarimeter was determined using non-polarized radiation of sources based on Cd-109, Am-241 and Ba-133 nuclides. This work is devoted to the experimental determination of the response of the physical model PING-P FM to polarized radiation.

2. Design of the physical model PING-P FM
The PING-P polarimeter should be capable of measuring linear polarization of x-ray radiation in the energy range of 20-150 keV. As mentioned above, the physical model PING-P FM represents the detector part of the polarimeter. It contains the scattering block surrounded by receiver detectors, as well as high-voltage power supply boards and preamplifiers [9].

The scattering block contains an array of three symmetrically arranged active scatterers, which are scintillation detectors based on paratherphenyl crystals ø35×30 mm and PMT’s of type R3886A. Scattered photons are registered by six CsI (TI) crystals ø45×5 mm viewed by R10131-01 PMT’s. Pulses from all detectors are analyzed by multi-channel amplitude analyzers.

Three scatterers and six receiver detectors form 18 measurement channels. Each channel is characterized by its preferred direction of registration of scattered radiation that coincides with the line connecting the centers of crystals of the corresponding detectors, and by its specific solid angle of registration that depends on the distance between the detectors. Since it is due to the block geometry, we have three groups of solid angles corresponding to near, medium, and far detector pairs and 18 preferred registration directions.

If radiation is not polarized, the registration efficiency for all pairs of the same type (close, medium, and far) is the same. For a polarized radiation, the registration efficiency depends on the angle between the plane of polarization of the incident beam and the preferred direction of registration of scattered radiation for the given pair. The stronger this dependence, that is, the greater the signal modulation when the plane of polarization of incident radiation rotates, the higher is the sensitivity of the instrument to polarization.
3. Experimental determination of the modulation depth (modulation factor)

For experimental measurement of the modulation factor of the physical model, an experimental setup was assembled. The layout is shown in Figure 1 and Figure 2. Polarized radiation was obtained by scattering non-polarized radiation with a photon energy of 59.5 keV from an Am-241 radioactive source. The polarizer is made of plexiglass (see Figure 1). It is located on the axis of the PING-P FM device at a distance of 25 cm from the input window so that the scattering angle is close to 90 degrees. The electric vector of the radiation incident on the device is perpendicular to the direction of the primary non-polarized beam. The Am-241 source together with the polarizer could rotate around this axis to change the direction of polarization (see Figure 2). The distance from the polarizer to the device was limited by the activity of the source used.

Figure 1. Experimental layout. Schematic view in vertical plane (not to scale).

Figure 2. Experimental layout. Azimuthal angles of the primary beam are shown.

The experiment was performed for three polarizer positions corresponding to the primary beam directions 0°, 30° and 60°.

As the result of measurement for a certain polarization direction of the incident radiation we have 18 count rates corresponding to the number of registration channels. Data for each pair type (near, medium, and far) should be analyzed separately. Thus we have 6 points to build the modulation curve for each type of pairs. Modulation curve is meant as the dependence of the count rate in the channel from the angle between the polarization plane and the predominant registration direction of the detector pair.

The measured counting rates were adjusted to take into account the individual sensitivity of each pair obtained with non-polarized radiation [9]. The data adjusted in this way for the three types of pairs is shown in Figure 3.

The modulating factor of the polarimeter $\mu$ is defined as:

$$\mu = \frac{(C_{\text{max}} - C_{\text{min}})}{(C_{\text{max}} + C_{\text{min}})},$$

where $C_{\text{max}}$ and $C_{\text{min}}$ are the maximum and minimum values on the modulation curve. Using the curves approximating the experimental data in Figure 3, with the formula (1), the following estimates of the modulation factors were found: $\mu_c = 0.519$, $\mu_m = 0.555$, $\mu_f = 0.570$ for close, medium and far types of pairs.

As expected, the modulation factor increases with increasing distance between the scatterer and the receiver detector.
Figure 3. Counting rates of three types of detector pairs as function of angle $\psi$ between the plane of polarization and the preferred registration direction for a pair.

It should be taken into account that in our experiment, the analyzed radiation has a polarization slightly less than 100% due to a number of reasons: a) multiple scattering in the polarizer; b) the finite size of the radiation source and the polarizer; c) limited distance between the polarizer and the device; d) the location of the detector-scatterers not on the axis of the device. A simple estimate based on Thompson scattering cross section shows the degree of polarization to decrease to 98% owing to beam divergence (\~ 6°). Therefore the corrected values (if the degree of polarization were 100%) of modulation factors are: $\mu_c = 0.530$, $\mu_m = 0.566$, and $\mu_f = 0.582$. Despite the rather dense layout of the detectors of the PING-M polarimeter, its modulation factor turned out to be no worse than for the RHESSI device, which has a modulation factor of 0.40 to 0.59 for an energy of 60 keV [8].

4. Evaluating the sensitivity of the PING-M device
The sensitivity of the polarimeter is determined by its effective area and the modulating factor. The minimum detectable degree of linear polarization is found as [10]:

$$MDP = (n_\sigma \mu_{100} N) (2(N+B)/T)^{1/2},$$

where $n_\sigma$ – significance level (number of sigmas), $\mu_{100}$ – modulating factor, $N$ – total count rate from radiation source, $B$ – total background count rate, and $T$ – exposure.

The background counting rate in interplanetary space in the receiver detectors can be estimated using data [11] to be of the order of 150 Hz in one detector or 900 Hz in all six detectors. The count
rate in the scatterer detectors can be assumed to be the same (150 Hz / detector). Taking into account the time gate for coincident pulses of 1.6 microseconds, an estimate of the total background in double coincidences in all 18 measuring channels of about 1 Hz is obtained. This value is negligible compared to the useful signal, and formula (2) is converted to the form:

$$\text{MDP} = \frac{2^{1/2}n_0}{\mu_{100}(N-T)^{1/2}}$$

where the notation is the same as in formula (2). Or, going to the effective area of the polarimeter and the intensity of the incident radiation:

$$\text{MDP} = \frac{2^{1/2}n_0}{\mu_{100}(S_{\text{eff}}I-T)^{1/2}},$$

where $S_{\text{eff}}$ is the effective area of the polarimeter, $I$ is flux density of incoming radiation.

To apply formula (4) in our case, we need to take the total effective area for all three groups of pairs as the effective area, and the average modulation factor with averaging weights proportional to the effective areas of the groups as the modulating factor:

$$S_{\text{eff}} = S_{\text{eff}}^c + S_{\text{eff}}^m + S_{\text{eff}}^f,$$

$$\mu_{100} = \frac{\mu_{100}^c S_{\text{eff}}^c + \mu_{100}^m S_{\text{eff}}^m + \mu_{100}^f S_{\text{eff}}^f}{S_{\text{eff}}},$$

where $S_{\text{eff}}^c, S_{\text{eff}}^m, S_{\text{eff}}^f$ - effective areas, $\mu_{100}^c, \mu_{100}^m, \mu_{100}^f$ - modulating factors for close, medium and far pairs, respectively.

Using the values of the effective areas obtained in [9] and the modulation factors given in the previous section of this work, we find $S_{\text{eff}} = 1.5 \text{ cm}^2, \mu_{100} = 0.543$. The estimated effective area relates to the energy of 59.5 keV, while modulation factors, in fact, are measured at 53.3 keV. We believe this inconsistency being of minor importance.

Flux density of hard x-rays with photon energy > 25 keV from solar flares of x-ray class X1 is in most cases between 5·10^2 and 5·10^3 photons/(cm^2s) [11]. Since the polarimeter is to operate at closer distances from the Sun down to 0.3 AU, a distance of 0.5 AU can be taken to assess the sensitivity. Using the formula (4), one can estimate the polarization measurement threshold for the observation time of 10 s (with a significance level of 1σ) for an X1-class flare as $\text{MDP}(1\sigma) = 1.5 \div 0.5\%$. The spectrum of solar x-rays is growing towards lower energies where the effective area of the instrument drops (by approximately an order of magnitude at 22 keV). But the area increases rather fast in energy range from 20 to 30 keV. Therefore we expect that for hard enough spectrum, a significant portion of photons will be registered with greater sensitivity and the necessary exposure for real x-ray spectra can be estimated by the same value as given above.

5. Conclusions

The results of an experimental study of the physical model using polarized radiation allowed us to determine the modulation factor of the PING-M polarimeter at the energy of 53 keV. The sensitivity of the polarimeter is determined by the modulation factor and the effective area. The PING-M polarimeter provides three groups of detector pairs with different distances between the scatterers and receivers (near, medium, and far pairs). Each type of a pair gives a contribution to the useful polarization signal according to its modulation factor and effective area. The greater the distance between the scatterer and the receiver, the greater the modulation factor, but the smaller the effective area (efficiency). The proposed design of the polarimeter allows us to achieve statistical accuracy of 1.5÷0.5% in measuring the polarization degree of x-ray radiation from class X1 flares with a time resolution of 10 s.

References

[1] Kotov Y D et al. 2016 Adv. Space Res. 58 635–43
[2] Kuznetsov V D et al. 2016 Geomagn. Aeron. 56 781–841
[3] Bai T, Ramaty R 1978 Astrophys. J. 219 705–26
[4] Guzman A B, Kudryavtsev I V, Charikov Yu E. 1996 Astronomy and Astrophysics. 308 924-8
[5] Melnikov V F, Charikov Y E, Kudryavtsev I V 2015 Geomagn. Aeron. 55 983–90
[6] Tindo I P, Ivanov V D, Mandel'stam S L, Shuryghin A I 1970 Solar Physics 14 204–7
[7] Bogomolov A V et al. 2003 Solar System Research 37 112–20
[8] McConnell M L, Ryan J M, Smith D M, Lin R P, Emslie A G 2002 Solar Physics 210 125–42
[9] Savchenko M I, Kruglov E M, Lazutkov V P, Skorodumov D V, Shishov I I 2019 Journal of Physics: Conference Series 1400 022041
[10] Novick R 1975 Space Sci. Rev. 18 389-408
[11] Tranquille C, Hurley K, Hudson H S 2009 Solar Physics 258 141-66