Search and identification of precursors of solar flares based on microwave observations of active regions

Elena Popova, Centro de Investigación en Astronomía, Universidad Bernardo O'Higgins, Chile, elena.popova@ubo.cl;

Dmitrijs Bezrukovs, "Ventspils International Radio Astronomy Centre", Ventspils University of Applied Sciences, Latvia, dmitrijs.bezrukovs@venta.lv;

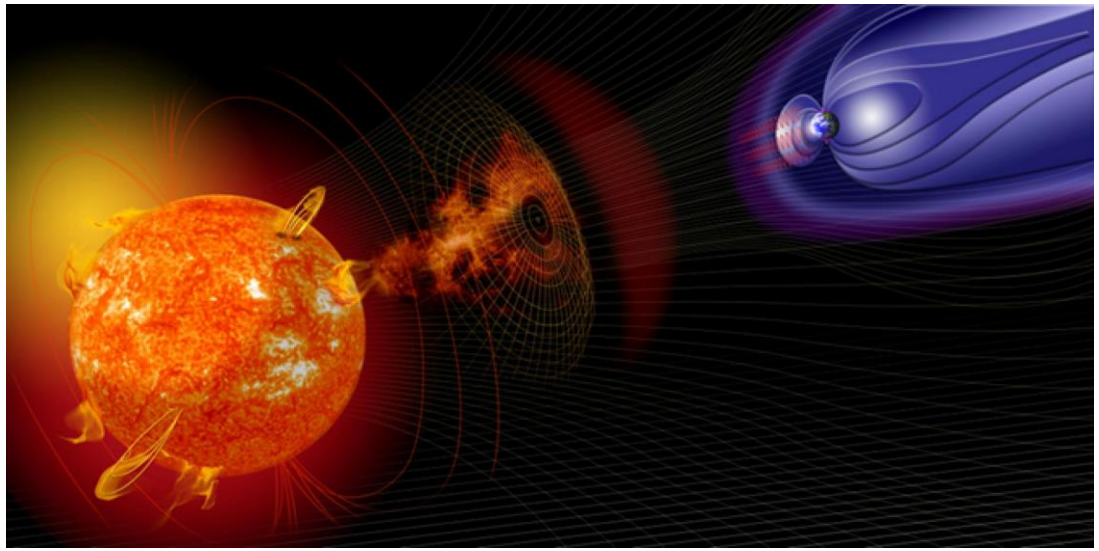
Vladislavs Bezrukovs, "Ventspils International Radio Astronomy Centre", Ventspils University of Applied Sciences, Latvia, vladislavsb@venta.lv;

Sergei Piskunov, Institute of Solid State Physics, University of Latvia, Latvia, piskunov@lu.lv;

Anatoli I. Popov, Institute of Solid State Physics, University of Latvia, Latvia, popov@latnet.lv

Solar flare activity before the main explosive phase

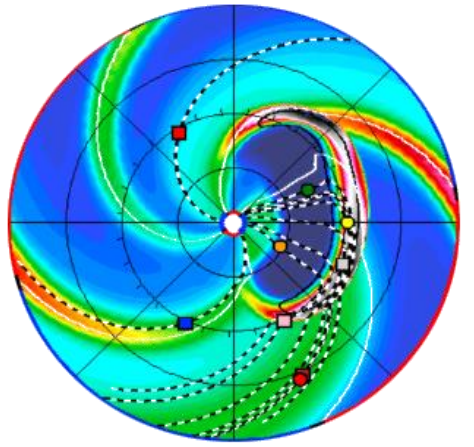
- Solar flare forecasts are made on the basis of detecting and interpreting precursors, as characteristic processes preempting the main phase the flares.
- Different methods of diagnostic is used in search for precursors: optical, UV, X-rays, magnetograms.



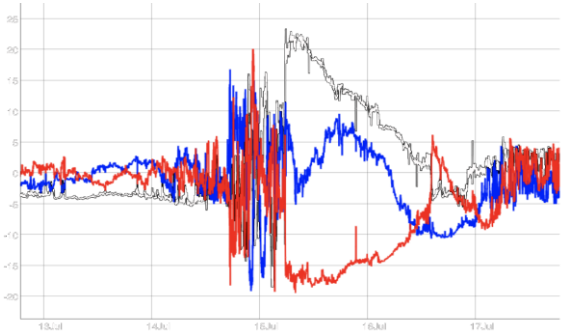
NASA

Predictions of solar events for forecasting of space weather:

- Modern physics-based models
- Availability of observational data
- Tools to predict space weather: models and data to feed them
- Archives of historical events



ENLIL simulation of an Earth-directed CME & the arrival of this CME at Earth



NASA

A month worth of Space Weather events

From February 18 to March 17, 2022

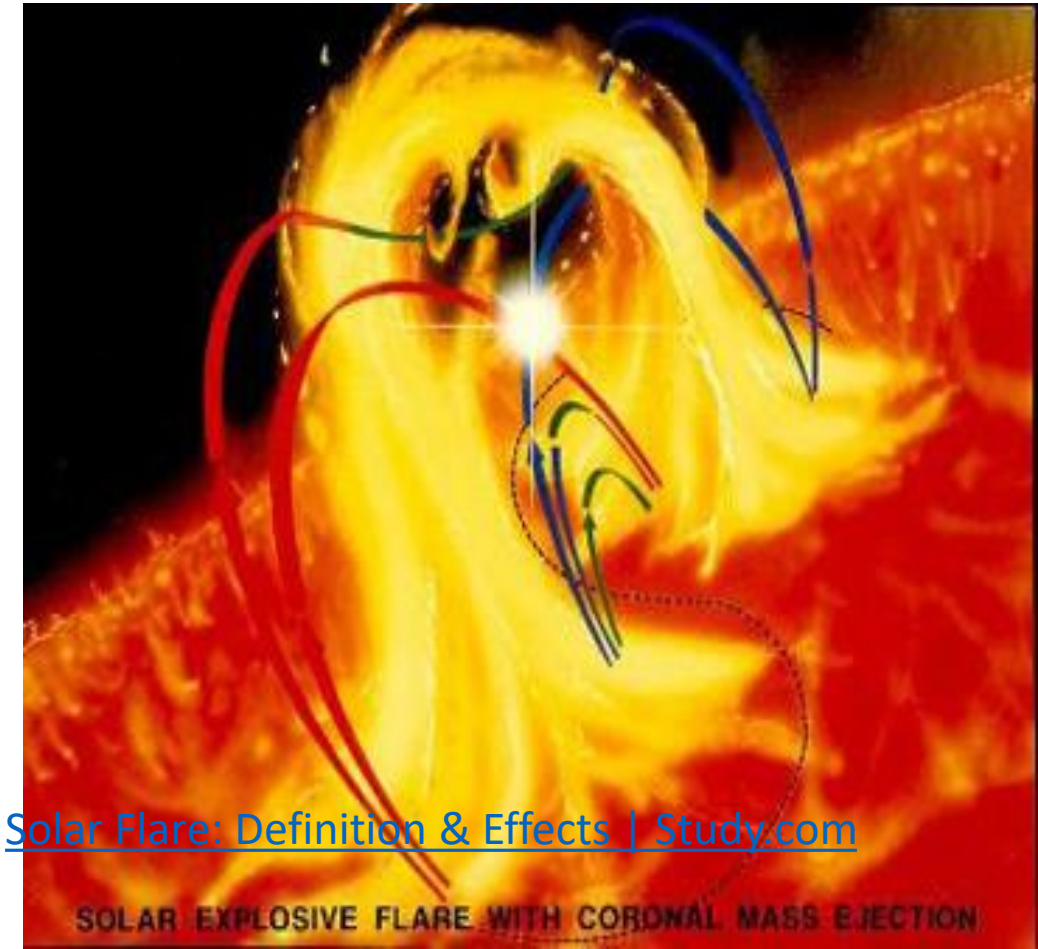
Activity Type	This Month	Details of space weather events
Numbered Active Regions	25	Magnetic Classification 7 Alpha (12950, 12952, 12954, 12967, 12968, 12969, 12970) 15 Beta (12943, 12946, 12948, 12949, 12951, 12953, 12955, 12956, 12958, 12959, 12961, 12962, 12963, 12964, 12966) 3 Beta-Gamma (12957, 12960, 12965)
Flares M-class or higher	5	M2.0 flare from AR 12958 (2022-03-02T17:31:00-FLR-001) M2.2 flare from AR 12964 (2022-03-11T22:13:00-FLR-001) M2.0 flare from AR 12965 (2022-03-14T08:35:00-FLR-001) M1.4 flare from AR 12965 (2022-03-15T12:33:00-FLR-001) M1.5 flare from AR 12965 (2022-03-15T22:39:00-FLR-001)
CMEs (>500 km/s)	14	5 Earth-directed 3 Mars-directed
Coronal Hole High Speed Streams	4	4 observed at L1 near Earth.
Interplanetary Shocks	10	5 observed at L1 near Earth.
Geomagnetic Storms (Kp > 6)	1	Max observed Kp = 6 (Moderate geomagnetic storm level) Associated with ICME: 2022-03-10T19:23:00-CME-001
Radiation Belt Enhancement	2	Both associated with HSS events
Solar Energetic Particle Events	0	

The Dynamo process of a magnetic field generation (via e.g. αΩ coupling accumulates the magnetic energy (of the toroidal field) inside the convective zone. Some of this magnetic energy can be carried by magnetic flux tubes floating up to the surface of the star and popping up in forms the spots (like in case of the Sun). The configuration of the magnetic field in the sunspot evolves over time and a flare appears when it becomes unstable.

Then the Flare releases a part of the free energy of the magnetic field through the mechanism of reconnection of field lines. From general considerations, the energy yield of the flare must be related to the size of the magnetic spot. There are stars with much larger spots than on the Sun, thus, with more powerful Flares.

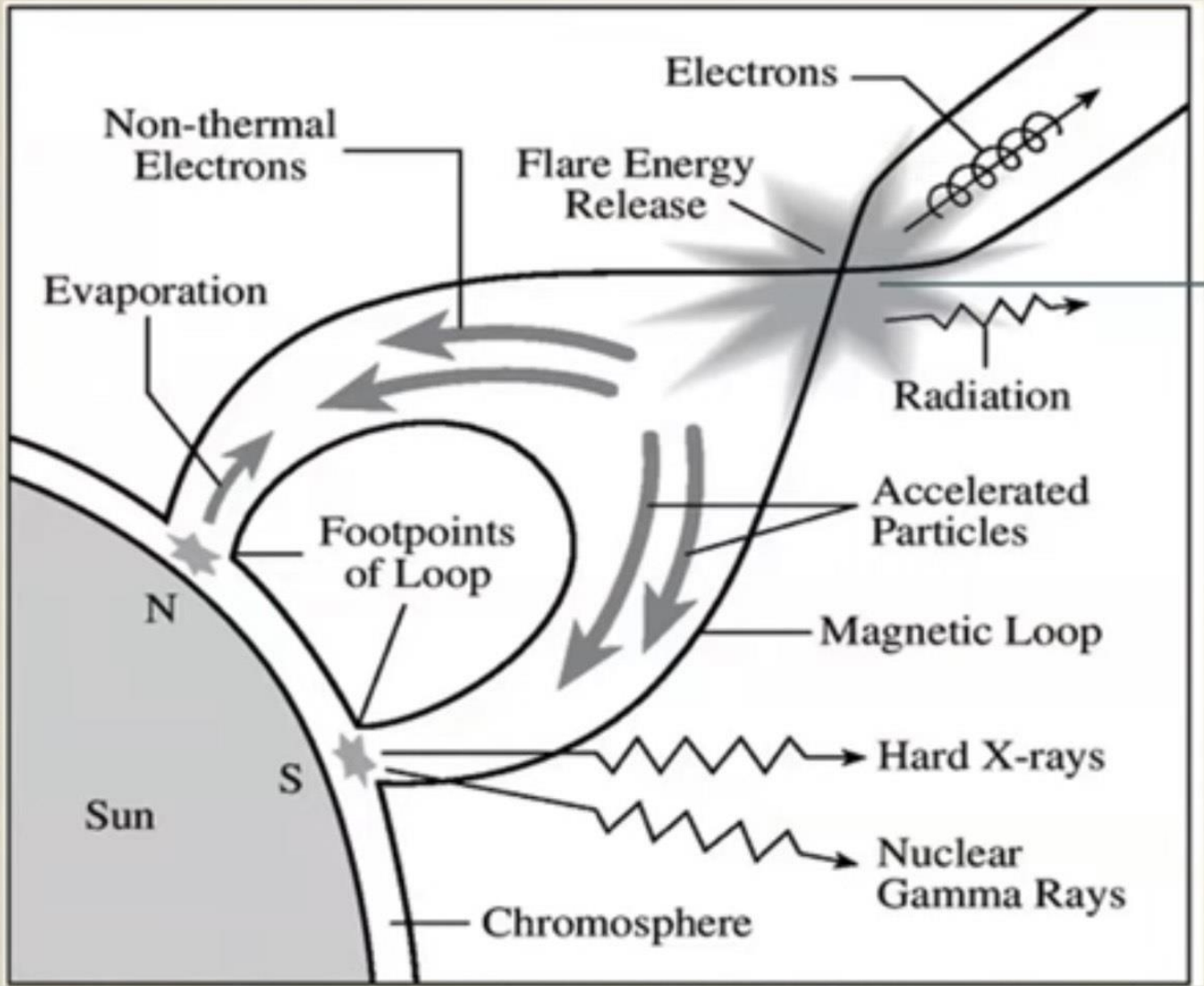
Such stars must exhibit faster rotation in order to support stronger αΩ-dynamo coupling.

Evolution of Active region and Explosive Phase



Solar Flare: Definition & Effects | Study.com

Standard model of solar flare



Soft X-rays

Accelerated electrons

Emission of microwaves (via transformation of electron plasma oscillations into electromagnetic waves and synchrotron radiation in a magnetic field)

Solar flare activity

- There are typically three stages of a solar flare
- First is the precursor stage, where the release of magnetic energy is triggered. Soft X-ray emission is detected in this stage.
- In the second or impulsive stage, protons and electrons are accelerated to energies exceeding 1 MeV. During the impulsive stage, radio waves, hard X-rays, and gamma rays are emitted.
- The gradual build up and decay of soft X-rays can be detected in the third, decay stage. The duration of these stages can be short as a few seconds or as long as an hour.

NASA

Types of precursors

- by the dynamics of sunspots
- by magnetograms
- by X-rays
- by microwave emission

Microwave range

- In (Wang et al, 2017), the authors use the large spatiotemporal resolution of the 1.6-meter New Solar Telescope, supplemented by new microwave data to search for flare precursors. Two variants of precursor brightening were found, which were initiated in a small-scale magnetic channel with numerous polarity reversals and enhanced magnetic fluxes and currents, which were located near the bases of shifted magnetic loops. Microwave scale studies have shown that these precursor emissions originate from the atmosphere. This suggests that a small-scale energy release in the lower layers of the atmosphere may be associated with the beginning of the main flare.
- In (Abramov et al, 2021) authors present a study of the spatial distribution of quasiperiodic oscillations of microwave emission in two active regions before M-class flares. Two events were studied: NOAA 11283 on September 6 and NOAA 11302 on September 25, 2011. The Nobeyama Radioheliograph (NoRH)daily observations were used at a frequency of 17 GHz. In both cases authors found the preflare wave trains of brightness temperature oscillations of microwave emission in active regions. The duration of wave trains is about 3–4 pulses. It was found that the source of oscillations was a compact zone in the active region, which coincides with the place of maximum brightness during a flare.

Nanoflares were invoked by E. Parker in 1972 as an explanation for coronal heating. Could they be behind the origin of Radio Precursors?

- They constitute a myriads of tiny (only tens of km) objects in the chromosphere.
- All processes in nanoflares are small copies of ordinary flares, where energy is released in the process of magnetic reconnection.
- If the nanoflares activity intensifies in an area of suspicious magnetic spot before a big flare, they might be detected by Solar Radio Telescopes as a kind of enhanced background or even as a bunch of smaller spikes.
- Until recently individual nanoflares were unresolvable. Now there are claims that Parker Probe was able to resolve them in a few cases / space scale around 60 km.
- Detailed systematic studies by solar radio telescopes, data accumulation, and correlation analysis with flares are needed in order to evaluate their role as precursors.

Microwave range

- The goal is to return to the regular use of solar radio astronomy data in the program for monitoring and predicting space weather. Unlike ground-based optical telescopes for solar astronomy and astrophysics, the radio range is practically all-weather (that is, does not depend on the weather).
- In addition, the presence of modern solar radio telescopes on almost all continents of the Earth could provide uninterrupted (24 hours a day) information on radio bursts.

Microwave range (cont.)

- Other very important factor is that the physics of the solar flare trigger mechanism includes accelerating processes of solar plasma particles and for radio astronomy, the electronic component of particle acceleration plays an essential role.
- The electron beams generated in the process of reconnecting magnetic field lines must transform a significant part of their energy into radio emission.
- One of the important mechanisms is that the electron beam first generates its own plasma oscillations of the coronal plasma and then in the process of coupling in the region close to the plasma resonance there is a local transformation of longitudinal plasma oscillations into electromagnetic ones.
- Nonlinear effects of the interaction of longitudinal vibrations with electromagnetic ones can also generate higher harmonics. The second basic mechanism for generating radio emission from the solar chromosphere and corona is the classical magnetobremsstrahlung (often referred to as synchrotron radiation).
- The combination of data related to the processes in which both mechanisms are involved makes it possible to determine the parameters of the electron beam and restore the local value and direction of the magnetic field in the radiation zone.

Microwave precursor- its likely origine

- In principle, the possibility of predicting a solar flare from the data of radio emission emanating from some zone of the Sun suggests the existence of a preliminary mechanism for electron acceleration before the onset of the main phase of the flare.
- Theoretically, one would expect that such local ejections of accelerated electrons could exist in the process of approaching the magnetic field geometry of the solar active spot to the explosive reconnection instability threshold.
- These could be the precursor- nanoflares from the active zone that appear before the main phase of the flare.
- In order to establish a causal relationship between possible precursors of this kind, it is proposed to prepare and implement a detailed program for collecting data from radio telescope and to study the correlation of precursor signals with the moments of occurrence of subsequent outbreaks of major flares.

Ventspils International Radio Astronomy Centre

- We propose to employ the infrastructure of Engineering Research Institute "Ventspils International Radio Astronomy Centre“ (VIRAC) of Ventspils University of Applied Sciences (Latvia) and, in particular, the radio telescope RT-32 for the regular search of solar flare precursors, with the prospect of implement a service for their long-term monitoring.

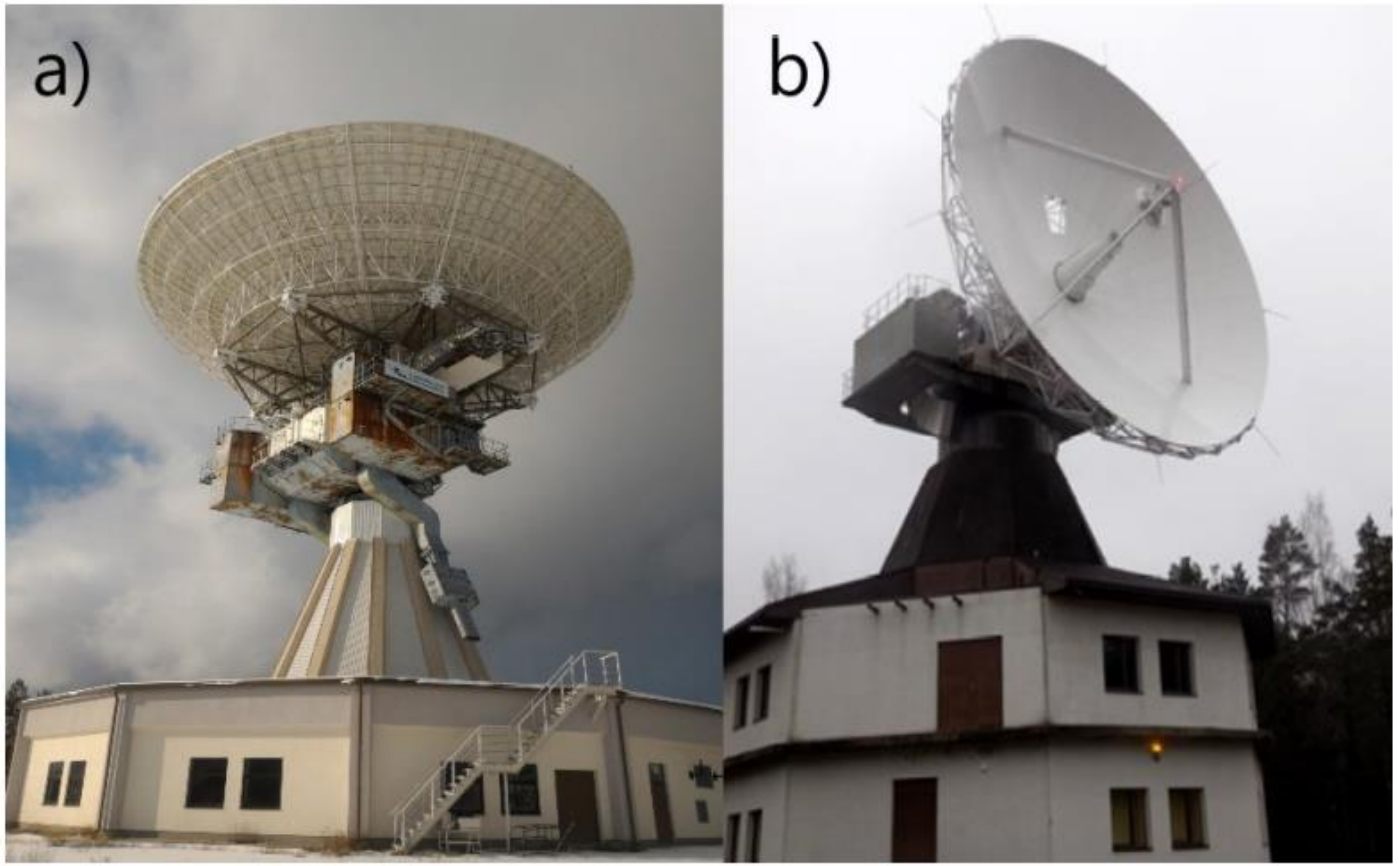


Figure 1. The VIRAC radio telescopes, located in Irbene site, Latvia: 32-metre antenna of RT-32 (a) and 16-metre antenna of RT-16 (b).

Some main parameters of spectral polarimeters are presented in the Table.

	SP3	LNSP4
Frequency range	6.3 – 9.3 GHz	4.1 – 14.3 GHz
Number of channels	16	12
Band widths	80-100 MHz	250-800 MHz
Polarization	RCP+LCP	RCP+LCP
S/N ratio (TquietSun/3*s*Tsysnoise)	~14-16 db	>22-24 db
Dynamic range	~18-20 db	>36 db
Sensitivity	~72 dbm	<80-82 dbm
Sampling rate	>80 sample/sec	~10 sample/sec
ADC resolution	16 bit	16 bit

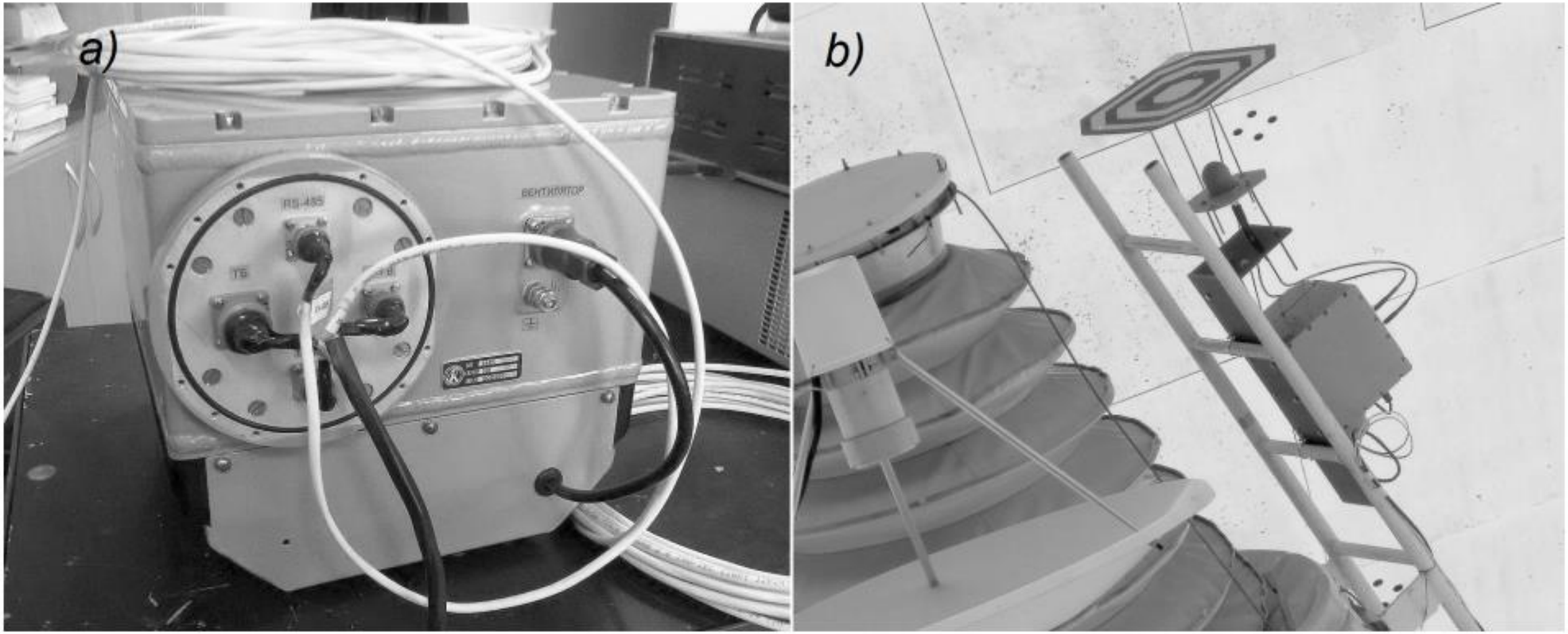


Figure 2. The multichannel spectral polarimeter LNSP4 under tests in the laboratory (a) and the temporary test installation of LNSP4+wide band feed+Fresnel lens set onto VIRAC RT-32 radio telescope antenna in the secondary mirror focal plane (b).

Summary

- We suggest that identifying what methodology and tools of VIRAC may be important for space weather monitoring, especially in the context of the search for precursors of solar flares.
- Our technique will also allow us to classify precursors according to the intensity of the flare that followed them, and we assume that we can predict the intensity of the flare by the type of precursor.