

Post-print on the Application of Coded-Aperture Imaging Methods for Coronal Energetic Neutral Atoms

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Abstract

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Full Text

Application of Coded Modulation Imaging Methods for Coronal Energetic Neutral Atoms

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This paper analyzes the scientific significance and observation methods of coronal neutral atom detection, proposes a coded modulation approach for coronal neutral atom imaging, and completes a preliminary instrument design based on scientific requirements. The instrument measures neutral atom energies from 0.5 MeV/u to 6 MeV/u with a field of view covering . It uses high-voltage electrostatic deflection plates to remove charged particles within the measurement range, employs m-sequence coded modulation grids and silicon semiconductor detectors to form the imaging structure, and integrates electronics to implement the complete instrument.

Keywords: Neutral atoms, Imaging observation, Coded modulation

Abstract

A general design of the Solar Neutral Atom Code Mask Imager (SONACOMI) is proposed. The instrument is designed to measure solar energetic neutral atoms emitted from solar flares or coronal mass ejections (CMEs), measuring the differential energy spectrum of ENAs between 0.5 MeV/u and 6 MeV/u with an ENA field of view covering . This instrument combines innovative sensor geometry, an m-series coded mask modulation aperture, and a combination of high-voltage deflecting plates for active and passive shielding of charged particles to obtain ENAs in space flight.

Keywords: Solar ENA, Imaging, Code Mask

Solar activity patterns, intensity, and periodicity profoundly influence the space environment around Earth. Observing solar activity to obtain information and provide early warning time for Earth has long been a research focus, including observations of solar X-ray flux and imaging [1,2]. In addition to electromagnetic radiation at various wavelengths, another major influence on Earth's space environment comes from charged particles transported through solar activities such as solar flares, coronal mass ejections (CMEs), and solar wind. These particles cause intense magnetospheric activities like magnetic storms and substorms when they reach Earth, damaging satellites, spacecraft, and other space assets. Observing the processes of energy and mass transport from the Sun to Earth to understand the correlations and patterns between solar activity and Earth-threatening events, thereby obtaining early warning and prevention methods for various terrestrial responses, has been a persistent scientific endeavor.

Solar Proton Events (SEPs) and CMEs are typical sources of solar influence on Earth. Some SEPs form directly at the solar source through flares, while others are accelerated by interplanetary shocks from CMEs [3,4]. By observing various particles released during SEP eruptions and CME events, we can investigate the transport, acceleration, and diffusion mechanisms of solar proton events and coronal mass ejections—tasks currently undertaken by instruments on satellites such as SOHO and ACE [5-8]. Since SOHO, ACE, and similar satellite instruments primarily measure charged particles that are modulated by electric and magnetic fields, the measured information represents only the local state at the instrument's location and cannot reflect the long-range transport state of CME processes. Researchers have proposed using neutral atoms to observe solar mass ejections [2], enabling observation of neutral atoms released during CME processes from Earth's orbital position to provide short-term, full-sky information about charged particle transport states during solar flares and CMEs, thus offering fundamental data for Sun-Earth environment interaction studies.

Space neutral atom observation methods employ collimators combined with imaging structures and semiconductor sensors to obtain the energy spectrum distribution, temporal distribution, spatial distribution, and directional distri-

bution of neutral atoms in space. Combined with appropriate space physics models, these measurements can be used to reconstruct the energy spectrum and directional distribution of various ions contained in the neutral atoms. Measuring the spatial distribution of neutral atoms requires instruments with spatial resolution capabilities. Approaches such as those used on CRRES and IBEX satellites utilize spacecraft platform scanning to achieve spatial resolution, but this results in low temporal resolution—for example, IBEX requires 2 days. Since acceleration and diffusion propagation mechanisms require the highest possible temporal resolution, instrument-based particle optical system design is needed to achieve high temporal resolution.

Imaging systems can be implemented through mechanical division, pinhole imaging, or coded imaging methods. Mechanical division suffers from complex structures and heavy weight, while pinhole imaging has low temporal resolution. Coded imaging represents an important method for coronal neutral atom observation. The following sections introduce the principles, design methods, and sensor design of coded imaging.

1.1 Generation and Characteristics of Coronal Neutral Atoms

During solar eruptive events, whether solar flares or CMEs, energetic ions collide with electrons, background tenuous gas atoms, or low-energy ions, capturing electrons to form neutral atoms. These neutral atoms retain the original energy and direction of motion of the ions, flying away from the Sun, with some reaching near-Earth space where they can be observed. On December 5, 2006, the STEREO satellite observed a solar flare eruption through its LET (Low Energy Telescopes) detector, which released large quantities of energetic neutral atoms. The ejection region in the corona exceeded 2 solar radii, with durations reaching minute-level timescales. The observed neutral atom energy spectrum spanned 1–10 MeV, as shown in Figure 1 Figure 1: see original paper. Observations from Earth's orbit show that the distribution of neutral atoms released from the corona is primarily within ± 5 degrees, as shown in Figure 1(b) [10].

Magnetic loop footpoint regions during solar flares, magnetic reconnection regions, and interplanetary shock acceleration regions in CMEs all contain energetic ions that undergo collision reactions with electrons () or ions () to produce energetic neutral atoms. However, after generation, neutral atoms continuously collide with heliospheric electrons and ions during flight, undergoing ionization reactions that progressively reduce their numbers along the path from the source region. This causes the flux observed by instruments to differ by orders of magnitude from the flux at the source region.

1.2 Observation Significance and Performance Requirements

Many mechanisms in the processes of energy and mass release from solar activity to the Sun-Earth space environment remain unclear, such as: whether shock-accelerated fast CMEs form SEPs ahead of or behind the shock, whether the

accelerating shock is quasi-parallel or quasi-perpendicular, and where the seed particles for SEPs originate [5-9].

Based on the spatial neutral atom energy spectrum distribution and observation angular distribution shown in Figure 1 [Figure 1: see original paper], the technical specifications for coronal neutral atom observation are as follows: - Energy range: 0.5 MeV/u to 6 MeV/u, with energy resolution $dE/E < 0.1$ - Field of view covering , with angular resolution of - Imaging temporal resolution better than 1 minute

2.1 Basic Methods for Neutral Atom Measurement

Measuring spatial neutral atoms and forming short-term spatial distribution maps constitutes “imaging.” This can be achieved through neutral atom measurement instruments themselves, as on the STEREO satellite, or through spacecraft platform scanning of space, as on the IBEX satellite.

Space contains various particles, including charged particles and occasional energetic neutral atoms. Therefore, the neutral atom imaging observation process must consider charged particle removal. Based on electromagnetic interaction principles, charged particle removal can employ electrostatic field deflection or magnetic field deflection. However, magnetic fields produce large deflection differences for different charged particles, while electrostatic fields reduce these differences, making electrostatic deflection the preferred approach.

Neutral atom energy measurement can utilize MCP assemblies or Si-PIN sensors. MCP assemblies are suitable for low-energy neutral atoms, while Si-PIN sensors are appropriate for higher-energy neutral atoms. Low-energy neutral atom measurement requires ionization before entering the MCP assembly sensor to facilitate measurement, whereas higher-energy neutral atoms can be measured directly with Si-PIN sensors, eliminating the need for a dedicated ionization component.

Combining electrostatic deflection structures with sensor assemblies forms the basic spatial neutral atom measurement unit, as shown in Figure 2 [Figure 2: see original paper]. Space electrons and ions passing through the deflection region are deflected by the electrostatic field and eliminated through collision with high-voltage electrodes. Since space ions have greater mass than electrons, they travel shorter distances, while neutral atoms are unaffected by the electric field and travel straight into the sensor.

The simple method for spatial neutral atom imaging uses multiple measurement units combined to form one-dimensional or two-dimensional imaging observations. Multiple units forming a one-dimensional linear array constitute one-dimensional imaging, while multiple units forming a planar array constitute two-dimensional imaging.

2.2 Principle of Neutral Atom Coded Imaging

Based on the field of view coverage and angular resolution requirements for neutral atom imaging, and considering that neutral atoms in space originate from spatial ions with low flux density, the measurement process requires the largest possible entrance area to obtain more effective sensor counts.

For imaging modulation of spatial neutral atoms, analogies can be drawn with modulation techniques for high-energy X-rays and gamma rays, including spatial modulation imaging such as coded aperture imaging or Fourier transform imaging, and temporal modulation imaging [11]. Coded imaging is relatively simple in structure and straightforward in principle among these methods. Coded imaging can be understood as an amplification of pinhole imaging, where the coded plate rearranges multiple pinholes according to specific requirements to allow neutral atoms from space to pass through in a regular pattern, thereby increasing the number of neutral atoms entering the sensor acceptance range, as shown in Figure 3 [Figure 3: see original paper].

Spatial neutral atom imaging can be analogized to high-energy ray imaging but differs in that the observed particle flux represents the instrument's location and requires further data inversion processing combined with other physical models to derive source region neutral atom parameters [12,13]. The coded imaging plate is a board filled with pinholes that allow neutral atoms to pass through, while other areas block them. The blocking region unit area equals the pinhole area, with pinhole distribution arranged in a predetermined pattern.

A simple model describing the coded modulation principle includes three components: the modulation pattern transmission function, the object distribution function, and the flux distribution function recorded by the observation sensor, given by expression (1):

where $*$ is the convolution operator and represents uncorrelated noise signals, referring to signals generated by non-observation signals passing through coded modulation, including electronic noise, etc.

Based on expression (1), the observation object reconstruction model from sensor observation signal data can be given by expression (2):

where is the reconstruction inversion function. The relationship between the transmission function and the reconstruction inversion function satisfies specific conditions.

3 Preliminary Design of Neutral Atom Coded Modulation Imaging

The design of a spatial neutral atom imaging instrument includes the overall instrument layout, collimator and deflection components, particle detection sensors, coded modulation pattern, and inversion algorithms.

The overall instrument layout primarily analyzes the applicable satellite platform characteristics, installation orientation, and overall instrument structure. The collimator ensures the formation of the instrument's observation field of view and also provides electrostatic deflection functionality for charged particle removal. Particle detection sensors measure neutral atom energy, with parameters such as sensitive area, thickness, and dead layer ensuring coverage of neutral atom energy and flux measurements. The coded modulation pattern and inversion algorithm form the core of spatial neutral atom coded modulation, with the pattern providing the modulation function and the inversion algorithm providing the data reconstruction pathway.

3.1 Overall Instrument Layout and Structure

A three-axis stabilized satellite platform is suitable for solar observation. The instrument must be installed on the Sun-facing side of the satellite, and since the platform cannot rotate, the instrument must form a two-dimensional imaging array. The entire instrument consists of two main sections: the electronics box and the sensor assembly, as shown in Figure 4 Figure 4: see original paper. The electronics box comprises front-end electronics and data processing units, while the sensor assembly consists of 10 imaging units, as shown in Figure 4(b), with each imaging unit separated by an 18-degree angle. Each imaging unit comprises electrostatic deflection plates, sensors, and coded grids, as shown in Figure 4(c), for observing spatial neutral atoms.

As shown in Figure 4(c), the grid in each imaging unit regulates neutral atom transmission, while the sensor measures incident particle energy. The combination of 10 imaging units forms a circular observation range, as shown in Figure 4(d), achieving an azimuthal resolution of 18 degrees.

3.2 Particle Detection Sensor and Energy Spectrum

Neutral atom energy detection characteristics are similar to those of charged particles. Upon incidence, neutral atoms quickly strip off extranuclear electrons and collide with the sensor, losing energy and generating electron-hole pairs in the sensor's sensitive region, which induces charge signals on both sides of the sensor.

Sensor sensitive region thickness must be selected based on the required neutral atom energy range. The sensor sensitive area must be set according to neutral atom flux density and electronic counting capability, and the number of sensor pixels must be determined based on overall design requirements.

As shown in Figure 5 [Figure 5: see original paper], measuring 6 MeV hydrogen neutral atoms requires a sensor thickness of at least 294.3 μm . Current sensor processes primarily provide thicknesses of 300 μm and 1000 μm , leading to the selection of a 1000 μm sensor thickness. Based on the coronal neutral atom energy spectrum function shown in Figure 1, the calculated flux density distribution ranges from 0.0122 to 5.5 $\#/\text{cm}^2$. The sensor single-pixel sensitive area should

be no less than $5 \text{ mm} \times 10 \text{ mm}$, with 32 pixels selected. The entire sensor layer has a length of 160 mm and width of 10 mm.

According to the previously proposed and energy resolution requirement $dE/E < 0.1$, the entire energy spectrum is divided into 25 energy channels, with count rates as uniform as possible across each channel, as shown in Table 1 .

3.3 Collimator and Deflection Length

Spatial neutral atoms arrive from all directions, requiring a collimator for direction definition. Various charged particles coexist with neutral atoms in space, necessitating deflection structures for charged particle removal, as shown in Figure 2.

Current high-voltage power supply devices can provide up to 5 kV in vacuum, so the design uses a deflection voltage of 5 kV. Based on the previously selected sensor dimensions, the deflection electric field width is 10 mm. The deflection ratio varies with deflection plate length, as shown in Figure 6 [Figure 6: see original paper]. As deflection plate length increases, the electron cutoff ratio also increases. When the deflection plate length increases to 0.28 m, the deflection ratio for 6 MeV electrons reaches 99%. When the length increases to 0.95 m, the deflection ratio for 6 MeV protons reaches 99%. Therefore, the collimator and deflection plate length is selected as 1.0 m.

As shown in Figure 7 [Figure 7: see original paper], protons with different energies emitted in a conical space at a 2.15-degree angle to the deflection plates undergo deflection by the electrostatic field between the plates during flight. For 1 m-long electrostatic deflection plates, protons with energies below 6.0 MeV can be deflected and absorbed, while some 6.5 MeV protons will escape the deflection plates.

3.4 Coded Modulation Pattern

The coded modulation plate selectively transmits spatial neutral atoms and represents the key component for coded modulation imaging. Plate material, thickness, and duty cycle are important parameters. The material must block charged particles and be machinable. The blocking capability ratios for aluminum, stainless steel, and lead plates show that lead requires the smallest thickness to block ions of the same energy but has the highest density and mass, along with machining difficulties. Aluminum requires the largest thickness, while iron requires moderate mass and is relatively easy to machine. Therefore, iron is selected as the coded modulation plate material. Blocking 6 MeV ions requires a thickness of 110 μm , so the coded modulation plate thickness is selected as 0.2 mm.

The spatial angular resolution of a coded modulation imaging system is determined by the coded plate aperture, sensor pixel size, and their spacing. The modulation code for spatial neutral atoms uses an 8th-order pseudo-random binary polynomial expression to generate a 511-length m-sequence code value, as

shown in Figure 9 [Figure 9: see original paper], which generates the 0-1 binary sequence for controlling grid “on/off” states for neutral atoms.

As shown in Figure 10 [Figure 10: see original paper], the coded modulation grid structure generated from the m-series produces a 0-1 binary sequence with 511 cells and a grid width of 0.52 mm.

The coded modulation plate dimensions are related to sensor size, with plate dimensions of 160×10 mm and a field of view of 10 degrees. The grid width, sensor pixel width, and their spacing determine the angular resolution in the radial dimension for spatial neutral atom imaging. As shown in Figure 11 Figure 11: see original paper, the angular resolution can be expressed as:

where θ is the radial spatial angular resolution, w is the grid cell width, p is the sensor pixel width, and d is the distance between the modulation grid and sensor pixel.

As shown in Figure 11(b), the relationship between the planar spacing of the coded grid and sensor and the spatial neutral atom radial resolution shows that resolution decreases as spacing increases. When the spacing is 0.6 m, the angular resolution can reach 0.48 degrees.

3.5 Electronics Processing Block Diagram

The electronics processing for the coronal neutral atom imager includes both sensor box and electronics box sections, as shown in Figure 12 [Figure 12: see original paper]. The sensor box section primarily provides high-voltage electrostatic deflection electrode voltage, sensor bias voltage, and power supply for ASICs performing front-end amplification, peak sampling, and amplification functions. The electronics box section mainly includes instrument power supply circuits, FPGA circuits with data storage RAM, and a MIL-STD-1553B module responsible for data exchange with the satellite platform.

This paper proposes using coded modulation methods for coronal neutral atom imaging observation and completes a preliminary instrument design. The instrument front-end uses high-voltage electrostatic deflection electrodes to filter charged particles and employs m-sequence coded grids combined with semiconductor sensors to form the imaging structure. This achieves higher count rates than direct isolation imaging or pinhole imaging methods, realizing a field of view coverage of degrees and angular resolution of for coronal neutral atoms.

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