Soft X-ray detectors for pulsar navigation

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Abstract. This paper summarizes the requirement of X-ray pulsar navigation and the development of X-ray detector. The difficulties of pulsar navigation in space environment are pointed out. The lack of detectors in terms of detection efficiency, time resolution and load is discussed. Finally, some suggestions are given for future research in X-ray pulsar navigation.

1 Introduction
As the human’s exploration of the space more in-depth, the current navigation technology cannot meet the requirement of high-precision navigation and autonomous navigation in the future. An autonomous navigation technology based on X-ray pulsars is considered to be the preferred solution to next-generation navigation technology and it becomes the important technology that space powers to compete to develop [1-6].

A pulsar is a highly magnetized, rotating neutron star or white dwarf, that emits a beam of electromagnetic radiation. The period of pulsar’s rotation is stable, and it is known as the most stable clock in nature. Therefore, the spacecraft can determine the time, position and attitude in high-precision by detecting the X-ray radiation of pulsars [7-9].

The pulsar navigation utilizes an X-ray detector carried on a spacecraft that records the pulsar radiation X-ray signal in a single photon measurement. Within a finite time, the pulse profile formed by the signal can characterize the radiation characteristics of the pulsars. Finally, the autonomous navigation of the spacecraft is realized by contour phase analysis and navigation algorithm [10].

The autonomous navigation of the spacecraft based on X-ray pulsars is expected to improve the autonomy of spacecraft operation and get rid of the dependence on earth navigation, which has important strategic research value and broad engineering application prospect.

However, practical pulsar navigation detection technology is extremely complex, the detector needs to have a large sensitive area, high efficiency, faster response time, better energy resolution and portable size. At the same time, it is necessary to solve the problem of how to efficiently detect very weak target signals in space complex environment. Although, the relevant research has been carried out for more than 20 years, these issues still need to be further studied [6].

2 The principles of detecting X-rays
X-ray detections use the interactions between X-ray and material to work. In the low energy region (E$_\gamma$ < 100keV), photoelectric effect plays a leading role:

$$\gamma + \text{atom} \rightarrow \text{atom}^* + e^-$$

While detecting the soft X-ray (the photon energy of which is about 1keV to 15keV) signals of Pulsars, the mainly interaction between the X-ray and the substance is the photoelectric effect.
When the photon of X-ray arrives at the detector, it collides with the atoms of the sensitive material in the detector and releases the energy proportional to the number of photons. The detector determines the number of the photons by measuring the current, energy or other physical quantities to obtain the information of the X-ray.

Since the essence of the X-ray is photon, the basic particle detector can be used to detect the X-ray. Common X-ray detectors include: proportional counters, scintillation detectors, microchannel plates, and semiconductor detectors. Combined with the application for pulsar navigation, more details will be described in following text.

3 X-ray detectors for pulsar navigation

3.1 Proportional counter

A proportional counter is a detector that uses gases as a detection medium. The detector converts the radiant energy into charge by ionization of the gas molecules. When the X-ray photon enters the gas detector and interacts with the gas molecules, the energy is completely lost in the working gas. The gas molecules are ionized by the energy to form positively charged ions and negatively charged electrons. These positive ions and electrons move to the cathode and anode, respectively, under the action of the internal electrodes of the detector. Finally, the amplified signal is collected in the collection side by the avalanche effect. Figure 1 shows the arrangement of gas flow proportional counter.

The proportional counter is a mature device. The output signal of proportional counter is large and the sensitivity is good. It is widely used in high-energy particle detection due to the advantages of simple structure and easy processing.

However, the space environment is complex. Micro-meteoroids in space may cause the proportional counter to leak. At the same time, the volume of proportional counter is large and it is difficult to be equipped with satellites. For example, the proportional counter was equipped to detect X-rays by US Navy Research Laboratory in "X-ray Astronomical Plan" in 1999 [11]. But unfortunately, the experiment eventually failed due to the leak in the detector [12]. Therefore, the solid detectors have become a focus on further research.

![Figure 1. The arrangement of gas flow proportional counter](image-url)
3.2 Scintillator detectors

Scintillator detectors are typically composed of scintillators, photomultiplier tubes, and corresponding electronic components. When the particles enter the scintillator, the incident particles lose energy. The scintillator atoms and molecules ionization or excitation to radiate a certain wavelength of light in the back-excitation process. The photons arrive at the cathode to release photoelectrons by photoelectric effect. Photoelectrons multiply in the photomultiplier tube and the voltage generated by the anode phones pulse finally. Figure 2 Shows the scintillation crystal and scintillation detector assemblies.

The scintillation detector is a detector that fairly matured and widely used. It has been invented for more than 100 years. The scintillator can be machined in a large size detector, so its detection efficiency is high and can reach several times of gas detector.

However, scintillator detectors are not suitable for use in space. For example, NaI and CsI are common scintillators. They have high efficiency of detection, but they are prone to deliquescence and their reliability is poor in space. BGO does not deliquescence but its efficiency of detection is only one-tenth of NaI. Recovering the efficiency and stability of the scintillator remains to be studied.

![Figure 2. Scintillation crystal surrounded by various scintillation detector assemblies.](image)

3.3 Microchannel plates

A microchannel plate (MCP) is a large array of high spatial resolution electron multiplier detectors with very high temporal resolution. Figure 3 shows the structure of microchannel plate. The microchannel plate is based on a glass flake, and the micropores are arranged in a hexagonal cycle with a smaller pore size than the space period on the substrate in a space period of several micrometres to ten micrometres. There are about a million micro channels on an MCP, and the secondary electrons can be multiplied and multiplied on the wall of the channel, and the working principle is similar to that of the photomultiplier tube.

MCP has time resolution of 1ns and it is suitable for rays of which energy ranges from 0.1keV to 10keV. MCP can work at room temperature so it eliminates the need for complex refrigeration installations. In addition, its structure is simple and it is easy to integration large enough.

However, limited by its poor energy resolution capability, no discrimination ability for particles and low detection efficiency for soft X-ray, the MCP meets many challenges to be applied to pulsar navigation directly. Therefore, some researchers use scintillators as photoelectric cathodes, combined with the MCP, in order to improve detection efficiency for soft X-ray [13,14]. The research shows the
detection efficiency is raised a little bit, although it is difficult to ensure that CsI does not deliquesce while used for large sensitive area.

\[ \text{Figure 3. The structure of microchannel plate} \]

3.4 Semiconductor detectors

A semiconductor detector in ionising radiation detection physics is a device that uses a semiconductor (usually silicon or germanium) to measure the effect of incident charged particles or photons. Semiconductor detectors have found broad application for recent decades, in particular for gamma and X-ray spectrometry and as particle detectors. While detecting the X-ray, X-ray photons enter the semiconductor detector, so that the semiconductor can produce a large number of electron hole pairs. The electrons migrate to the anode under the applied voltage. Voltage signal generated after amplification through the collection.

The charge-coupled device (CCD) is a two-dimensional array of micro-semiconductor detectors. Each unit of CCD consists of a positive electrode, a negative electrode, and a thin layer of silicon dioxide sandwiched there between. When a positive voltage is applied to the positive electrode, a potential well of electrons is formed into the semiconductor for collecting ionized electrons. The charge collected on each small electrode is transferred to the main electrode by means of periodic power-up method, and the position information, energy information and time information of the incident photon are obtained.

CCD’s position resolution is very high, while the time resolution is low to several milliseconds so that the researchers used swept charge device (SCD) instead of CCD. It can work to discard the location of X-ray photon information to read faster. The first generation of SCD is CCD54, and it was carried on SMART-1 in 1999 and C1XS in 2008. The second generation of the SCD is CCD236. The structure of CCD236 is shown as Figure 4 and it was carried on Chandrayaan-2 which will be launched in 2018 \[^{15,16}\].
The silicon drift detector (SDD) is another X-ray radiation detectors used in x-ray spectrometry (EDS) and electron microscopy. Like other solid state X-ray detectors, silicon drift detectors measure the energy of an incoming photon by the amount of ionization it produces in the detector material. Its chief characteristics compared with other X-ray detectors are high counting rates and comparatively high energy resolution. Its time response to 1ms and expensive for large sensitive area limit its application for X-ray pulsar navigation.

There are also other types of semiconductor detectors using new materials and new structures, such as graphene field effect transistors, still in the primary study for X-ray pulsar detection $^{[11,17]}$. The field effect of graphene shown is as Figure 5. The structure of a graphene field effect transistor is shown as Figure 6.
4 Conclusion
The space environment is extremely complex for X-ray pulsar navigation. The target signal used for navigation is extremely weak and the measurement time is limited, that it is very demanding for pulsar navigation detection. Gas detectors are prone to leaks and are too bulky. Scintillator detectors are prone to deliquescence, and their reliability is poor in space environment. The detection efficiency of MCP is to be improved. The time resolution of CCD and SCD is not enough.

In summary, researchers need to combine the application of navigation, and strive to improve the energy resolution of the detector, time resolution, target particle type identification of the detection method, sensitive material and structure, multi-signal screening and other aspects of technological innovation, to ensure that the target weak signal large area efficient collection with inhibiting the background radiation noise.

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