Analysis of the Principle and Applications of Infrared Detectors in Cosmology

Jiangtian Chen *

International Department of Hangzhou NO.14 High School, Zhejiang, China

* Corresponding author: lara_vassallo@elcamino.edu

Abstract. As a matter of fact, infrared detectors are widely used and applied in cosmology detections. On this basis, this paper provides a comprehensive analysis of the principles and applications of infrared detectors in the field of cosmology. The paper discusses the two main types of infrared detectors: bolometer arrays and photon detector arrays, explaining their underlying principles and highlighting their applications in astronomy. It also presents the advancements in infrared detector technology, such as the use of different materials and the development of large-scale bolometer arrays. The paper further discusses the significant achievements made by various institutions in the field of infrared astronomy, including the discoveries based on detection result from SOFIA and WISE. Overall, this paper offers a comprehensive overview of the principles and applications of infrared detectors in cosmology, providing valuable information for enthusiasts in the field. These results shed light on guiding further exploration of space detectors.

Keywords: Infrared detector, bolometer, astronomy.

1. Introduction

Since the construction of the first city, the creation of the oldest symbols, and the establishment of leadership in tribes, humans have exhibited an unwavering fascination with the celestial bodies that adorn the night sky. Their varying luminosity, mysterious configurations, and ethereal presence above all other existences have encouraged numerous endeavors to comprehend their intrinsic nature. Initially, astronomy served religious rituals, agricultural practices, and timekeeping, relying solely on the unaided human eye. However, during Han Dynasty in early imperial China, a systematic approach to star observation facilitated by rudimentary instruments including armillary spheres and gradients was invented, marking a significant advancement in this field [1]. Subsequently, the inventions of various mechanical and optical instruments, such as observatories and telescopes, greatly advanced the precision of astronomical measurements, therefore, bestowing upon humanity a broader perspective of the universe. After a deeper insight into properties of light in nineteenth century, an era remarked by numerous astronomical and cosmological discoveries started. In 1864, Miller and Huggins made the groundbreaking discovery that certain stars possess distinct spectra which unveil the celestial bodies' elementary compositions [2]. Their evolutionary approach of dissecting light into spectra served as a catalyst for further researches, inspiring numerous observations utilizing infrared and ultraviolet detectors in the subsequent century.

In 1965, Arno Penzias and Robert Wilson discovered the cosmic microwave background through their measurements of microwaves, furnishing pivotal evidence for the advancement of cosmology [3]. In 1968, Eric Becklin and Gerry Neugebauer published their observation results of intense infrared radiation emitted from the galactic center, indicating intricate activities happening within this region [4]. Following the launch of the Infrared Astronomical Satellite (IRAS) in 1983 [5], a plethora of captivating findings were gleaned through spaceborne instruments orbiting beyond the barrier of atmosphere. The close correlation between infrared radiation and heat has made infrared detectors indispensable components in modern astronomical explorations. Thanks to progress in semiconductor technology and precision manufacturing techniques, a significant advancement in infrared detector technology occurred in the past several decades. Based on their underlying principles, infrared detectors can be generally categorized into two types: bolometer arrays and photon detector arrays.

A bolometer array consists of numerous bolometers that detect fluctuations in heat caused by infrared radiation. These bolometers generate electronic signals used for image generation. Bolometer arrays are widely applied in various scenarios, including astronomical observations, medical diagnostics, and night vision. Current research in this area focuses on evolving the bolometers' material and advancing the data acquisition techniques. For instance, Domizio et al. have proposed a systematic approach to data acquisition and system control for large-scale bolometer arrays [6]. Additionally, Ukibe and his colleagues have explored the use of alloy materials to improve the performance of bolometer arrays [7]. A photon detector arrays utilize semiconductor materials whose properties change in response to infrared radiation. Recent studies have displayed considerable enthusiasm in improving these materials and refining the underling phenomena. While many researchers continue to enhance the structure and design of photon detector arrays based on HgCdTe [8], others (e.g., Martyniuk et al. [9]) have proposed alternative solutions that may offer similar or even superior performance. The continuous advancements in infrared detector technology have opened up new possibilities in astronomical research, enabling scientists to delve deeper into the mysteries of the universe. Numerous institutions from around the world have made significant achievements in the field of infrared astronomy. The IRAS, scanned 96% of the sky and discovered about 350,000 infrared sources. Other noteworthy projects include Japan's Infrared Telescope in Space (IRT) and the European Space Agency's Infrared Space Observatory (ISO), which have also provided a wealth of data. These observations have significantly enhanced our understanding of phenomena such as interstellar medium, star formation regions, and dark matters [10].

This paper aims to provide a comprehensive discussion of the general phenomenon, structure, and products of both photoconductor arrays and bolometer arrays. While many papers in this field can be difficult to comprehend for readers without a professional background, this paper strives to clarify terms, avoid redundancy, and provide clear explanations. Hoping researchers seeking a brief understanding of this unfamiliar field will benefit from this paper.

2. Photon Detector Array

2.1. Basic Descriptions of Detectors

The photon detector array is a collection of multiple photon detectors that can detect electromagnetic waves. When light interacts with the detector, the photons, which are the fundamental particles of light, interact with electrons in detector, causing a minute fluctuation in electric signal as the electrons gain energy and momentum from the photons. This electric signal is then processed through amplifiers and used for imaging. Due to quantum effects, photon detectors are highly sensitive to the wavelength of light, allowing them to effectively collect specific information without being significantly affected by other light. To ensure accurate operation and faster response, these detectors are often cooled to low temperatures, presenting various engineering challenges.

Photon detectors find wide applications in various fields. In communication, they are used to detect light signals transmitted through fiber optic cables. In spectroscopic analysis, they are used to detect light of different frequencies. By utilizing the photon detectors' ability to convert light at specific wavelengths into electric signals, engineers incorporate them into arrays to transform invisible infrared radiation into visible images. The properties of a photon detector are determined by its materials and structures. Common detector materials include HgCdTe, silica, quantum wells, and quantum dots. Detectors made from different materials can detect infrared radiation at different wavelengths [11].

2.2. Principal of HgCdTe Detectors

Mercury cadmium telluride detectors, also known as HgCdTe detectors, are a type of infrared detector that operates based on photoconductivity. These detectors are made from a compound semiconductor material consisting of mercury (Hg), cadmium (Cd), and tellurium (Te) [12]. The

composition of the material can be modified in certain way to adjust the bandgap of detection, making it possible to sense infrared radiation with various wavelengths. HgCdTe detectors absorb the infrared photons through the unique property of material. When an infrared photon is absorbed by the HgCdTe detector, it excites an electron from the valence band to the conduction band, generating an electron-hole pair. The excited electron is free to move and thus improves the conductivity of the material.

The change in the material induces a tiny electrical signal. To detect the generated signal, the HgCdTe detector is typically hybridized with a readout integrated circuit (ROIC). The ROIC is responsible for collecting and processing the signals from the individual pixels of the detector array. The HgCdTe photodetector layer is closely attached to the ROIC, ensuring efficient utilization of the ROIC area [12]. The performance of HgCdTe detectors is influenced by various factors including the quantum efficiency, operating temperature, and dark current. Because of the high absorption coefficient and relatively low thermal generation rate, HgCdTe detectors can operate at higher temperatures compared to infrared detectors based on another phenomenon. This allows the reduction in size, weight, and power consumption of the overall infrared system, since HgCdTe detectors only require thermoelectric coolers instead of cryogenic cooling systems. Furthermore, advancements in HgCdTe technology have led to a reduction in pixel pitch, allowing for higher resolution, enabling finer details in the infrared image. These advancements have made HgCdTe detectors a popular choice for space-based astronomy sensors.

3. Bolometer Array

3.1. Basic Descriptions of Detectors

Bolometer array is based on the principal of transforming energy from infrared radiation to thermal energy. While other detectors sense the individual photons, the bolometers cannot; instead, bolometers measure the total energy absorbed. This property makes them highly sensitive and capable in detecting infrared radiations with low intensity. Bolometer array consist of multiple individual bolometer which are arranged in grid-like pattern. Each of them has two parts: absorber and heat sink. When the radiation is absorbed by absorber, the temperature increases and resistance changes. Then, the difference in resistance in measured and amplified to produce signals which will be processed into images.

Bolometers' capability in operating submillimeter and millimeter spectral range makes them ideal for observing cold astronomical entities including dust clouds and distant galaxies. Bolometer arrays can also be used in conjunction with other types of detectors to cover a wide range of wavelengths. In recent year, advancements in technology have make the large-scale bolometer arrays possible. These arrays are offering detailed and comprehensive observation results. They are often used in space-based telescopes and ground-based observatories to study the most distant and faintest objects in universe.

3.2. Advantages of MEMS-based Bolometer Array

With the develop of Microelectromechanical Systems (MEMS), bolometer arrays show several advantages over photon detection arrays. In the work authored by Frank Niklaus and his colleagues, a systematic approach in micronizing bolometer is provided [13]. The MEMS technology is the integration of mechanical, electrical, and optical components on a microscopic scale. Through semiconductor manufacturing techniques, fabricated tiny devices and structures are assembled together into functioning devices including sensors, actuators, and other microscale components that can sense, manipulate, and interact with the surrounding environment.

One of the key advantages of MEMS is its small size and compactness. The microscopy feature of the MEMS devices allows the miniaturization of a complex systems, enabling the development of highly integrated and portable devices that can be easily incorporated into aerospace applications which have extremely strict limitation on weight. Another advantage is low power consumption. Due to their small size, MEMS devices require significantly less power to operate compared to their

macro-scale counterparts. This low power consumption makes MEMS devices ideal for battery-powered applications, as it extends the battery life and reduces the need for frequent recharging or replacement. This feature is critical for future space-based infrared detectors located at L2 point where sunlight might be blocked by earth [10].

MEMS also offers the advantage of scalability and cost-effectiveness. The manufacturing process including photolithography and etching are highly scalable and compatible with mass production techniques. This scalability allows for the relative economic mass-production. In another world, the ability to produce MEMS devices in large scale also contributes to the reduction of manufacturing costs. Nevertheless, MEMS devices exhibit similar performance with their macroscopy counterparts. They often possess high sensitivity, precision, and reliability due to their small size and the integration of multiple functionalities. In summary, the advantages of MEMS include small size, low power consumption, scalability, cost-effectiveness, and high performance. These advantages make MEMS-based bolometer array extremely competitive in future astronomical exploration projects which involves the use of detectors on satellites.

4. Facilities And Detection Result

4.1. Wide-field Infrared Survey Explorer (WISE)

Completing the entire sky scanning for two times by 2011, WISE is definitely one of the most remarkable detectors in human history of space exploration. Till now, the data acquired through WISE is still being studied by numerous astronomers. Based on the observation of WISE, Daniel Stern et al. made the discovery that a simple mid-infrared color criterion, $W1-W2 \geq 0.8$, can effectively identify both unobscured (type 1) and obscured (type 2) active galactic nuclei (AGN). This criterion makes the identification of a much larger number of luminous AGN easier than traditional methods which are biased towards only unobscured AGN. In addition, the authors explored the properties and demographics of WISE-selected AGN candidates. They identified a high percentage of AGN candidates with a reliability of 95%. The spectroscopic redshift analysis revealed that the median redshift of the WISE AGN candidates was 1.11. These findings provide valuable insights into the multiwavelength properties and redshift distribution of AGN, contributing to a better understanding of their nature [14].

4.2. Stratospheric Observatory for Infrared Astronomy (SOFIA)

SOFIA is a specially designed Boeing 747SP airplane which carries a 2.7-meter reflecting telescope [15]. It is capable in avoiding the effect of Earth's infrared-blocking atmosphere by flying at the height of around 40,000 feet. The telescope carried are able to operate a wide range of infrared radiation. Also, it can be repaired and updated during the periods when the aircraft landed. This feature makes it even more capable for specific researches comparing to the space-based telescopes. One of the most famous observation results performed by SOFIA is the insights into the Helix Nebula. Fig. 1 shows the colored image of the Helix Nebula from Hubble Space Telescope and spectral energy distribution of WD 2226-210 [16]. The researchers discovered evidence of infrared excess emission linked to the white dwarf at the nebula's center. However, the SOFIA observations did not detect a point-like source precisely at the position of the white dwarf, challenging the previous understanding of the dust temperature and morphology based on Spitzer observations and photometry. Since the sensitivity of the SOFIA observations was limited, they imposed strong constraints on the total brightness of the excess emission at longer wavelengths. Further investigation is required to unravel the nature of this intriguing excess emission from the central white dwarf of Helix Nebula [17].

In Nicola Schneider and his colleagues' work about interstellar cloud, the authors discovered a fascinating phenomenon in the Cygnus X region though the observation of SOFIA. The Fig. 2 shows Composite image of Cygnus X obtained by NASA's Spitzer Space Telescope, with SOFIA's upGREAT ionized carbon data overlaid in blue, green, and red [18]. They used the heterodyne array receiver upGREAT to observe the 158 μm line of ionized carbon, [CII], mapping the distribution of

[CII] in the area. They found that the strongest emission in both [CII] and CO tracers was concentrated in the -3 km/s component from the DR21 ridge and the 9 km/s component from the W75N cloud. These bright clouds and PDR regions were embedded in a pervasive medium emitting in [CII], which was not or only slightly visible in CO. This observation reveals a kinetic interconnection between the [CII] emission and the molecular clouds, concluding that spiral density waves can lead to the formation of massive OB clusters. This finding has significantly enhanced our understanding of molecular cloud formation in the Milky Way and other galaxies [19].

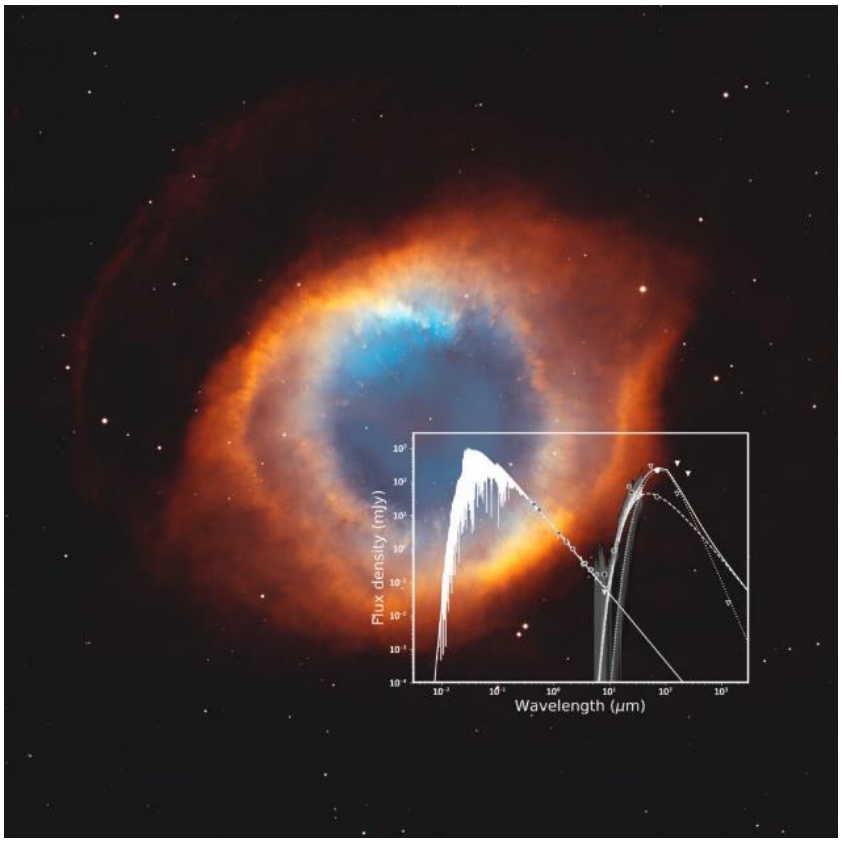


Figure 1. Helix Nebula.

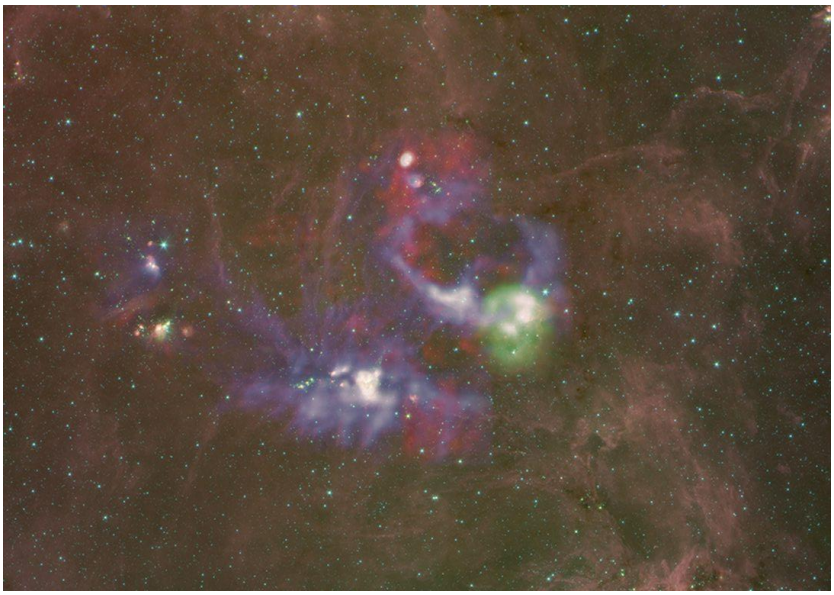


Figure 2. Cygnus X

5. Future Outlook

Though infrared detection arrays have provided valuable data for astronomers, several unneglectable short comes limit the future development of them. First, the cost of infrared detectors remains at a high level. Since the atmosphere blocks infrared radiation from reaching the surface of earth, modern infrared telescopes are usually deposed at high atmosphere, low earth orbit, or L2 point. Thus, the cost of transportation and maintenance remains extremely high. Second, large scale bolometer array shows high dependency on liquid helium. However, due to the desperate low level of helium contained in crust and its irreplaceable role in many other fields including manufacturing and medical care, Helium should be preserved for more urgent purpose such as life-saving. For solving the problems in future, aerospace technology and evolvement in infrared detection principal plays a critical role.

In the future, the development of infrared telescopes will involve several aspects. Firstly, in order to observe more distant and detailed celestial objects, improvements focus on larger apertures and higher resolutions will take place. Secondly, there will be an expansion of the wavelength coverage, aiming to obtain more comprehensive astronomical information. Advanced detector technologies including the use of superconductor and quantum effects will be applied to enhance sensitivity and detection efficiency. Furthermore, larger fields of view and higher observation efficiency will be designed to simultaneously observe a greater number of celestial objects. In short, the future development of infrared telescopes will aim at more precise and comprehensive instruments, enabling deeper exploration of the miseries in universe.

6. Conclusion

To sum up, this paper presents a comprehensive review of the theories and applications of infrared detectors in the field of astronomy. The detection methods in the infrared range are categorized into two types: photon detection arrays and bolometer arrays. Photon detection arrays rely on the conversion of incoming infrared photons into electrical signals, while bolometer arrays measure the temperature rise caused by the absorption of infrared radiation. The paper provides a brief explanation of the working principles and highlights the benefits of each type of detector. The paper also discusses the applications of infrared detectors in astronomy, focusing on two notable telescopes: the Wide-field Infrared Survey Explorer and the Stratospheric Observatory for Infrared Astronomy. While the paper acknowledges that it does not cover all recent infrared telescopes and their detection results, it provides a conclusive and understandable review of the field of infrared astronomy, serving as a valuable resource for enthusiasts seeking an overview of the theories and applications of infrared detectors in astronomy.

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