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The Main Groups of Photosynthetic Bacteria and Photosynthetic Pigments

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Abstract:

Photosynthesis is one of the most important process on today's Earth, which provides most of the energy source of the Earth's biosphere, changed and shaped the atmosphere and oceans in early days of the Earth. Photosynthetic bacteria are a kind of prokaryotic microorganism that can assimilate or dissimilate by using light energy as an energy source and organic or inorganic matter as the electron donor for assimilation or heterocytosis, which can be divided into Cyanobacteria, Purple bacteria (PB), Green bacteria (GB), Aerobic anoxygenic photosynthesis bacteria (AAPB) and others. In this paper, the literature on photosynthetic bacteria in recent years is reviewed and combined with the latest astrobiology research, revealing the photosynthetic pigment composition of different photosynthetic bacteria. Cyanobacteria contain Chlorophyll (Chl) for the absorption and transfer of light energy including Chl a, CHl b, Chl d, carotenoids and phycobilins, of which chlorophyll b and chlorophyll d are not contained in all types of cyanobacteria, PB contain BChl a or BChl b, GSB contains photopigments BChl a, Chl a, and BChl c, d, or e, GNSB contains photopigments BChl a and/or BChl c, and AAPB mainly contain BChl a. Understanding how Photosynthesis evolves, what kinds of photosynthetic pigments and how do it function could provide a new insight into the origins of life and are beneficial to detection of extraterrestrial life and potential habitable planets.

Keywords: Photosynthetic bacteria, Photosynthetic pigment, Cyanobacteria, Astrobiology.

1. Introduction

Photosynthetic bacteria (PB) are a kind of prokaryotic microorganism that can assimilate or dissimilate by using light energy as an energy source and organic or inorganic matter as the electron donor for assimilation or heterocytosis. PB are widely distributed in various aquatic habitats, and their community composition varies significantly depending on different environments [1]. PB can be classified into photoautotrophs and photoheterotrophs according to nutrient patterns, or into oxygen-producing photosynthetic bacteria and non-oxygen-producing photosynthetic bacteria (APB) according to the types of substrates and photosynthetic products [2]. PB usually contain different amounts of pigments for photosynthesis, ranging from chlorophyll a to e and bacterial chlorophyll. The photosystem formed by the pigments of different photosynthetic bacteria is also different, which makes different photosynthetic bacteria in the way of life, suitable light wavelengths and distribution [3].

The concept of oxygen-producing photosynthetic bacteria is now mainly referred to by the cyanobacteria group. In the second edition of Berger's Manual of Systematic Bacteriology, the phylum of Cyanobacteria covers all kind of cyanobacteria species. Cyanobacteria appeared early, in the previous literature were believed to have appeared as early as 3.5-3.3 billion years ago, and began oxygen-producing photosynthesis at 2.7 Ga ago, releasing oxygen to the atmosphere and oceans [4-5]. Due to their ability to utilize water as an electron donor, cyanobacteria can use light energy to synthesize organic matter while releasing oxygen as a by-product [6], which gives cyanobacteria a huge competitive advantage [7]. Since there was a gap of 500 to 1 billion years between the emergence of cyanobacteria and the Great Oxidation Event, cyanobacteria are also thought to have been one of the main factors in the Great Oxygenation Event 2.3 Ga ago (GOE) [6, 8].

Anoxygenic Phototrophic Bacteria (APB) are a large group of microorganisms capable of using inorganic or organic matter as an electron donor for photosynthesis without releasing oxygen. Yang summarized and concluded the taxonomy of APB, and divided the main non-oxygen-producing photosynthetic bacteria into five groups: green non-sulfur bacteria, green sulfur bacteria, purple bacteria, aerobic bacteria containing bacteria chlorophyll a and Heliobacteriaceae [2]. Vera Thiel, Marcus Tank, and

Donald A. Bryant used omics to classify photosynthetic bacteria into 9 groups: Cyanobacteria, Purple sulfur bacteria, Purplenonsulfur bacteria, Aerobicanoxygenic phototrophic bacteria, Chloracidobacterium thermophilum, Gemmatimonas phototrophica, Heliobacteria, Chlorophototrophic (Chlorobi), Chlorophototrophic (Chloroflexi) [9]. Non-oxygen-producing photosynthetic bacteria can complete photochemical reactions through a single photosystem, using substances other than water as electron donors (often sulfur or sulfur compounds), and through a set of circular electron transport chains to achieve energy assimilation and synthesis of ATP.

The origin of life on Earth is a major unresolved scientific question. The study of the possible forms and evolutionary pathways of life on early Earth will help to understand the process of life formation and contribute to the search for similar life on exoplanets with similar environments. Based on previous research in Earth science, the atmosphere and oceans of the early Earth had low oxygen content and were generally reductive [10]. A reasonable assumption is that early Earth life should have been able to survive in a low-oxygen environment. At the same time, most of the energy in the modern earth ecosystem comes from the solar energy fixed by photosynthesis, and the existing photosynthetic bacteria each carry the original, different, suspected multiple independent origin of the photosystem and different photosynthetic pigments, especially the cyanobacteria have two sets of photosystems to complete the oxygen-producing photosynthesis, which is more similar to the photosystem in today's chloroplasts [3]. The study of pigment and ecology of photosynthetic bacteria will help to understand the origin, adaptation and evolution of pigment among different photosystems, and bring new insights into related astrobiology studies.

In conclusion, the photosystem and ecological distribution of existing photosynthetic bacteria will be reviewed in this paper, and their main significance will be expounded in combination with the latest astrobiology progress.

2. Cyanobacteria

2.1 The taxonomy of Cyanobacteria

Cyanobacteria are a large group. In the second edition of Berger's Manual of Systematic Bacteriology, cyanobacteria are grouped together in the class Cyanobacteria under the phylum cyanobacteria. Some scholars have proposed that Prochlorophyta should be set up to show its morphological and structural differences from cyanobacteria, and that Prochlorophyta is a branch of primitive cyanobacteria evolution. Although there were some structural differences between Prochlorophyta and cyanobacteria, such as the absence of phycobilites, the prochlorophyta hypothesis was subsequently falsified and the prochlorophyta was reclassified into cyanobacteria. At present, only the cyanobacteria group of photosynthetic bacteria can carry out the photosynthesis of oxygen release. The current class of cyanobacteria is divided into five subsections in the first volume of Berger's Manual of Systematic Bacteriology, Second edition. Considering the morphology of cyanobacteria varies greatly, the research work is often carried out by genus and species. on the NCBI website.

2.2 The photosynthetic pigments composition of Cyanobacteria

Cyanobacteria contain pigments for the absorption and transfer of light energy including chlorophyll a (Chl a), chlorophyll b (Chl b), chlorophyll d (Chl d), carotenoids and phycobilins, of which chlorophyll b and chlorophyll d are not contained in all types of cyanobacteria [11]. Unlike existing eukaryotic algae and embryonal plants, cyanobacteria do not contain formed chloroplasts. The photosynthetic pigments of cyanobacteria are found in protoplasmic membrane structures called photosynthetic lamellae. The composed of phycobilins and proteins, which are called phycobilisomes (PBS) line on this protoplasmic membrane, absorbing light energy and transferring it to the PSII [7]. Fig.1 shows the schematic diagram of the photosynthetic system. The carotenoids contained in cyanobacteria are mainly echinenone and myxoxanthophyII. These carotenoids can protect cell from photodamage.

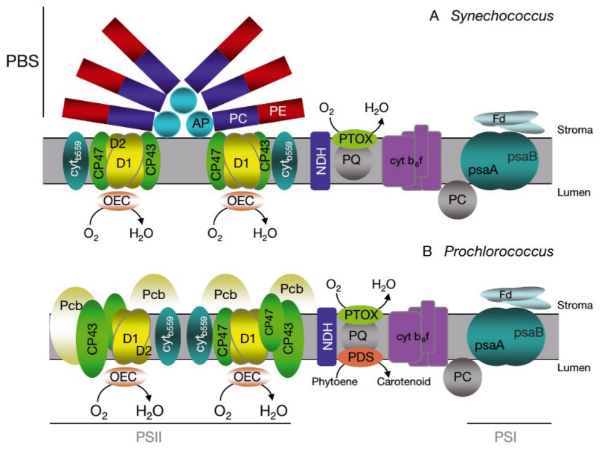

Fig. 1 The construction of two different types photosystem in cyanobacteria [12].

The work of G. M. Berg has shown two different photosystems present in cyanobacteria, Synechococcus with PBS and Prochlorococcus without PBS. PBS absorbs light in the range of 500-640nm[7]. This helps compensate for the low absorption of chlorophyll in this wavelength region, allowing cyanobacteria to use light energy more efficiently and live in darker and deeper locations[13]. Phycobilinsomes in cyanobacteria are regulated by light quality and growth conditions, green light can inhibit phycoerythrin synthesis, red light can inhibit phycocyanin synthesis.

Although most living cyanobacteria lineages live in oceans, estuaries, or lakes, some cyanobacteria can live in relatively extreme and less common areas, such as underground caves[14]. These cyanobacteria contain chlorophyll d or chlorophyll f as an unusual compensation in low light conditions[11, 15]. The pigment purification and testing of cyanobacteria Acaryochloris sp. NBRC 102871 by Nagao showed that the cyanobacteria photosystem was different from P700 and P680 photosystems, with the maximum absorption peak at 740nm, which was called P740 by the authors. In addition, the new species Chroococcidiopsis thermalis which was found by Nürnberg contains chlorophyll f has extended the absorption peak of chlorophyll to 745nm. Both of them breaks the limit of photosystem I and photosystem II. Fig.2 shows structure and absorption spectra of five different Chls[7].

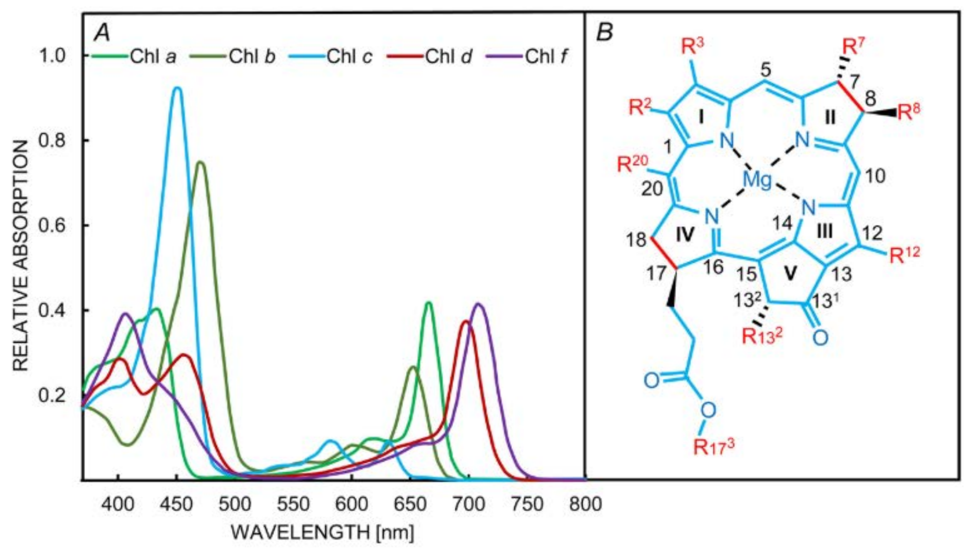

Fig. 2 (A) The absorption spectra of five Chls. (B) The chemistry structure of Chls [7].

3. Anoxygenic photosynthetic bacteria

Anoxygenic photosynthetic bacteria are also a very large group. In fact, different groups of photosynthetic bacteria are not closely related to each other. According to the sensitive of oxygen, these bacteria can be divided into Anaerobic and Aerobic bacteria. Purple sulfur bacteria, Heliobacteria. Purple non-sulfur bacteria, Chlorophototrophic (Chlorobi) and (Chloroflexi) are anaerobic, while Chloracidobacterium thermophilum, Gemmatimonas phototrophica are aerobic, which are also called Aerobic anoxygenic photosynthesis bacteria (AAPB). Each of these groups contains only one set of photosystems, which is significantly different from cyanobacteria.

3.1 Purple bacteria

Purple sulfur bacteria (PSB) and purple non-sulfur bacteria (PNSB) are two different types of Purple bacteria. They produce carotenoids that aid in photosynthesis and thus appear in darker colors, such as purple or yellowish brown. These carotenoids absorbing and reflecting could use infrared (IR) radiation, from 750 to 1100 nm [16]. In the second edition of Berger's Manual of Systematic Bacteriology, purple bacteria were distributed in more than 30 families of α-Proteobacteria, β-Proteobacteria and γ-Proteobacteria of Proteobacteria. Although the name PNSB literally means that this group of bacteria cannot use sulfides, both PNSB and PSB can use sulfides. The photosynthetic pigment of these bacteria is no longer chlorophyll, but a substance called bacterialchlorophyll (BChl). Purple bacteria contain BChl a or BChl b [9]. Studies have shown that bacterial chlorophyll appears to have originated earlier than chlorophyll, a hypothesis that remains to be tested [3]. For purple bacteria, the main electron donor is H2S and the carbon source is CO_2. They can also use organic matter in the surrounding environment. Some purple bacteria are also able to use Fe^{2+} as electron donors[9].

3.2 Green bacteria

Similar to the situation of purple bacteria, green bacteria are also divided into green sulfur bacteria (GSB) and green non-sulfur bacteria (GNSB). However, difference between green sulfur bacteria and green non-sulfur bacteria is significant. In second edition of Berger's Manual of Systematic Bacteriology, GSB belongs to the phylum Chlorobi and contains 20 species in 4 genera, GNSB belongs to the phylum Chloroflexi and contains 10 species in 8 genera. GSB is an obligate photoautotroph, which means it can only live in light. GSB contains photopigments BChl a, Chl a, and BChl c, d, or e [17]. GSB can also use sulfide and Fe2+ as electron donors, which may be one of the causes of iron deposition zones in the ocean [18]. The photosynthetic pigments in GNSB are BChl a and/or BChl c (d).

3.3 Aerobic anoxygenic photosynthesis bacteria (AAPB)

Aerobic anoxygenic photosynthesis bacteria (AAPB) is a general term for a large group of bacteria. In fact, This large group of bacteria can be divided into smaller groups based on the differences in physiological structure. Generally, AAPB is a group that is unable to produce oxygen and can use reducing organics as electron donors for photosynthesis in an aerobic environment. Although these bacteria can receive light energy using bacteriochlorophyll, they still need to obtain organic matter from the outside as carbon source to maintain their growth and reproduction, which means they are hetertroph bacteria[1, 9]. Most of AAPB belong to α, β and γ- Proteobacteria, some of them belong to Acidobacteria and Gemmatimonadetes[1, 9]. The photosynthetic pigment of AAPB is BChla, which is a kind of substance with a structure similar to chlorophyll. Its main absorption wavelength can reach more than 800nm, which helps the distribution of AAPB in deeper water[19].

4. Photosynthetic bacteria and Astrobiology

The astrobiology implications of photosynthetic bacteria are actually obvious. The most important thing for a planet's ecosystem is the producer, meaning the species that can receive energy and produce reducing matter or organic matter for other living things to consume. It is vital for life to be able to capture energy and maintain the stability of its systems, often from stars or deep-sea hydrothermal vents. The photosystem in the cell is the key to receiving radiation from the star. The study of the relatively primitive structure of photosynthetic bacteria and the complex and diverse composition of photosynthetic pigments can help us understand the origin and evolution of photosynthetic pigments and photosystem. In turn, studying photosynthetic bacteria on Earth can allow us to understand how chlorophyll and photosynthetic pigments such as bacterial chlorophyll adapt to and use sunlight and protect their molecular structures from being destroyed by photon. The spectral absorption and reflection maps of photosynthetic pigments on Earth have been plotted.

Coelho selected 23 species of purple bacteria for culture and measured their absorption and reflection spectra. They produced several charts simulating cloud cover, snowball Earth, the ratio of the sea to land on modern Earth and drought conditions. The results show that when photosynthetic bacteria cover a certain surface area of the planet, photosynthetic pigment specific absorption peaks can be displayed in the entire surface reflection map, which has important significance for deep space exploration missions. At the same time, since most of the stars in the Milky Way are red dwarfs, this means that the light emitted by this star will be mainly concentrated in the red region. This exceeds the wavelength absorption range (700nm) of the main chlorophyll on Earth: chlorophyll a[7]. In the experiment, the bacterial chlorophyll a and b bands of PSB and PNSB have obvious absorption characteristics at 800-805nm and 850-855nm, and PNSB can utilize light energy with wavelength of 1010nm. Meanwhile, the cyanobacteria that reported by Nurnberg contains chlorophyll f were able to absorb longer wavelengths of light. These suggests that purple bacteria and some cyanobacteria can thrive on planets orbiting red dwarfs, and also optimize possible future extraterrestrial life detection projects [13, 16].

5. Conclusion

Photosynthetic bacteria are a large and ancient group. The study of their diversity and antiquity involves the most important and equally ancient reaction on Earth: the origin of photosynthesis. This article discusses recent research on oxygenic and anoxygenic photosynthetic bacteria, especially the taxonomy and photosynthetic pigments of cyanobacteria, purple bacteria, green bacteria and AAPB are discussed, and the latest astrobiology literature is reviewed. Cyanobacteria, whose photosynthetic pigment is mainly Chl a, is the only group of photosynthetic bacteria on Earth that uses water as electron donor for oxygen-producing photosynthesis, which leads to the generation of Great Oxygenation Event. Purple bacteria, green bacteria and AAPB mainly contain BChl a and carotenoids, and the pigment composition of some populations can support them to thrive in low light intensity and long wavelength environment. The cyanobacteria population in the cave is particularly adapted to the far-red light environment, and these cyanobacteria and some purple bacteria can thrive on planets orbiting red dwarf stars (M-Star) in similar light conditions.

In the process of potential future colonization of other planets, some suitable Photosynthetic bacteria can act as a good starting point for modifying the environment. Studying the absorption spectra of these photosynthetic bacteria could help future space missions identify potentially habitable planets with life. These Photosynthetic bacteria on Earth still needs to be study.

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