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Introduction to Oceanography

Literature Review: Bioluminescence in the Ocean

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ABSTRACT

When sailors first noticed the eerie glowing waters beneath their ships at night, the phenomenon was attributed to monsters of the deep or mysteries of the unknown. According to Kaan Biron of the University of British Columbia, serious scientific attempts to understand the cause of this luminescence in organisms was not in progress until sometime during the mid 1600's (2003). Now it is known that bioluminescence has evolved several times throughout evolution, and is present in thousands of species ranging from bacteria and unicellular protists to squids and even some sharks (Haddock et. al. 2010). In many ecosystems, it has a powerful influence on marine communities and the behavioral ecology of species, particularly in the deepest parts of the ocean. This paper examines our current understanding of what bioluminescence is and in which species it is found, the history of how that understanding progressed, and more recent advances involving varied aspects of bioluminescence.

I. Introduction

According to the New World Encyclopedia, bioluminescence can be defined as: "The production and emission of light by a living organism as the result of a chemical reaction during which chemical energy is converted to light energy" (2008). This chemical reaction occurs in the presence of oxygen between a protein called luciferin and an enzyme known as luciferase. It has been observed in thousands of species, including bacteria and fungi as well as marine animals. Though the functions of bioluminescence are still studied and often debated, three major ones which are the most commonly reported are predation, defense, and communication (Biron 2003).

How It Works

The mechanism for bioluminescence works slightly differently for individual species of organisms. In most cases, the reaction involves the oxidation of the protein luciferin, a light-emitting molecule. The luciferin interacts with an enzyme; it can be either a luciferase or a photoprotein, depending on the species. In an article titled “Bioluminescence in the Sea”, Haddock and his colleagues describe a photoprotein as a “…luciferase variant in which factors required for light emission (including the luciferin and oxygen) are bound together as one unit” (2010). To produce light, the photoproteins need to bind to a specific cofactor or ion. This causes a conformational change in the protein, and is a way in which an organism can carefully control its light emission – an important ability in situations where being illuminated could potentially be dangerous. These photoproteins and the luciferases are extremely varied and highly species-specific, having derived from many evolutionary lineages.

In sharp contrast to the diversity of luciferases, only four luciferins are responsible for the majority of the light reactions in the oceans. One in particular is known as coelenterazine, and is the light-emitting protein in at least nine phyla – including protozoans, jellyfish, crustaceans, mollusks, arrow worms, and vertebrates. It is known that some species obtain this luciferin from their diet, with small crustaceans as the most likely source in the food chain. However, the ultimate origin of marine luciferins including this one remains unknown (Haddock et. al. 2010).

In addition to the complexity and diversity of technical details, another intriguing feature of these chemical light reactions is their incredible efficiency. Unlike so many energy conversion reactions, bioluminescence is nearly 100% efficient, according to R. Aidan Martin of the ReefQuest Centre for

Shark Research. Martin writes that “Virtually all of the energy generated by the luciferin-luciferase reaction is converted into light with almost none lost in heat or sound production” (1992).

Presence in Diverse Species and the Symbiotic Relationships between Species

Among marine animals, bioluminescence is present in a multitude of species spanning a large variety of taxa. These include bacteria, fungi, dinoflagellates, annelids, ctenophores (comb jellies), cnidarians, mollusks, crustaceans, echinoderms, insects, and fish (New World Encyclopedia 2008). It is nearly entirely absent from freshwater species, with the exception of some insect larvae and a freshwater limpet, according to Haddock. The reasons for this are not fully understood, but scientists note that the ocean has several properties which may have made it more favorable for the evolution of luminescence, including the comparatively stable environmental conditions, its optical clearness in comparison with rivers and lakes, and the existence of habitats which exist in complete and continuous darkness (Haddock et. al. 2010). In support of this last point, Biron reports that the majority of species in the ocean that do bioluminescence are generally found below 800 meters (2003).

Haddock and his colleagues also point out in their article that “The distribution of bioluminescence across the major taxonomic groups does not appear to follow any obvious phylogenetic or oceanographic constraints”. It can be found in siliceous protists but not calcareous foraminifera or coccolithophorids. Alternately, it can be found in calcareous echinoderms and mollusks, but absent in siliceous phytoplankton (diatoms). Also, parasites are overwhelmingly non-bioluminescent overall, with the exception of hyperiid amphipods (2010).

Creatures which are bioluminescent can be divided into two distinct categories, as Martin reports in his article. One is the group of species which have self-luminous organs called ‘photophores’, which are complex eye-like structures embedded in the skin. In these species, light is reflected through a ‘lens’ and clear outer covering, producing a gentle and even glow. The second category includes those species which essentially ‘borrow’ their luminosity from bacterial symbionts. In these cases, bags of bioluminescent bacteria are kept and nurtured by the host organism in exchange for the ability to luminesce (Martin 1992). Contrary to popular belief, it has actually been found that the majority of bioluminescent organisms generate their own light, and it is rarely due to bacterial symbionts (Haddock et. al. 2010).

Functions of Bioluminescence

As stated earlier, three of the main functions of bioluminescence for marine organisms are predation, defense, and communication.

A great example of how predation is an important utility of bioluminescence can be seen in the deep-sea angler fish. The light organ of this fish dangles in front of it in a lantern-like fashion. It contains a bacterial species related to the genus Vibro, and very effectively attracts unsuspecting prey straight towards the front of the fish (Biron 2003). Another example, described in the New World Encyclopedia, is the ‘cookiecutter’ shark. This species uses its bioluminescence for camouflage, while a small patch on its underbelly remains dark. To large predatory fish such as tuna and mackerel, the spot appears to be a small fish. As they come near to attack it, the shark strikes.

A slightly similar mechanism is employed by dinoflagellates for defense. When a predator of the plankton comes through the water, the dinoflagellate senses the motion and immediately luminesces. This works to attract larger fish to the area, when then consume the plankton’s would-be predator.

In a different system, some organisms have actually evolved the ability to use their bioluminescence in a similar way to how squid use ink. Certain crustaceans and squid use bioluminescent chemical mixtures or bioluminescent bacterial slurries to produce a cloud of luminescence, confusing or repelling a potential predator while the organism escapes to safety (New World Encyclopedia 2008).

Communication as a function of bioluminescence is most clearly observed in fireflies, but can also be seen in some marine organisms. The mating system of the Caribbean ostracods has been most well-studied. According to Haddock, “Ostracods show species-specific patterns of signaling, [and] complex three-dimensional mate-following behavior....” In addition, the shallow flashlight fish called *Photoblepharon* apparently has been shown to use its large light organ for interspecific communication, and scientists speculate whether the lure of the anglerfish may also function as a form of mate-finding.

II. Historical Perspective

Though sailors have been witnessing bioluminescent organisms in the oceans for ages, the cause of the light was not known until the advent of the microscope and the advances of modern science (Biron 2003). Yet even during the time when they remained a mystery to scientists, bioluminescent marine organisms seem to have captivated the interest and attention of many.

Human Interactions with Bioluminescent Organisms in History

The most common occurrences in which humans viewed bioluminescence throughout history were when sailors observed brilliantly luminescent bow waves or the glowing wakes of surface ships. The causal organisms were most likely dinoflagellates, or single-celled algae, which can number many hundreds per liter. They become mechanically excited, and therefore produced light with the ship’s passage overhead or even by the movements of porpoises and other fish (Haddock et. al. 2011).

During the era of the great Greek philosophers, Aristotle and Pliny noticed that damp wood and the flesh of dead fish appeared to luminesce. Since they could not explain the cause of this observed phenomenon, people during this time often made fairy-tale-like assumptions involving monsters or creatures of the deep (Biron 2003).

Further east, mariners in the Indian Ocean reported moving for hours through a sea glowing with a soft white light as far as the eye could see. This “milky sea” is a rare phenomenon resulting from bioluminescent bacteria, which occur nearly everywhere around the world.

In 1492, as Christopher Columbus approached the coast of North America, he reported seeing what he described as “candles moving in the sea” (as reported by Martin 1992). Biologists suspect he was witnessing the mass mating ritual of the bioluminescent Bermuda fire worm, which is a small, bottom-dwelling polychaete which swarms near the ocean surface at night during the summer.

Many years later, during World War II, Japanese soldiers began to collect ostracods and utilize them, according to Haddock. These organisms are only a couple millimeters long, but are capable of emitting a very bright light. They are often referred to as “seed shrimp” or “clam shrimp” because of their structures. Some specimens of these animals, collected in 1944, are remarkably still glowing after more than 60 years sitting at room temperature. The soldiers would crush a few of the dried organisms in their palms and use them as light at night – bright enough to read by, but not bright enough to be spotted by the enemy during the war. A large harvesting effort took place around this time, in which the little animals were collected in large numbers and dried out on the beach (as reported by Haddock et. al., 2011).

Scientific Advances in the Understanding of Bioluminescence

Though Aristotle and Pliny observed the luminescence of dead fish many centuries before, it took until the 1830’s for the German scientist G.A. Michaelis to discover that the effect was due to something living (as reported by Biron, 2003). In the 1850’s, naturalists demonstrated that the glow in the wake of boats was caused by multitudes of single-celled dinoflagellate animals, particularly the species *Noctiluca* (Martin 1992). It was not until the year 1885 that the French physiologist Raphael Dubois first isolated the light-producing chemicals present in clams (as reported by Biron, 2003).

More scientific advances drove the understanding of bioluminescence further in the 1900's. The luciferin protein of ostracods was first examined in the 1950's, according to F. Tsuji (1955, as reported by Haddock et. al. 2010). It was ultimately crystallized and characterized by Shimomura et. al in 1957, making it one of the first chemically well-understood luciferins of a marine organism. Kato et al. demonstrated in 2004 (as reported by Haddock et al. 2010) that ostracods synthesize their luciferin from tryptophan, isoleucine, and arginine, though the details of the actual process are still unknown. This version of the luciferin protein is found mainly in cypridinid ostracods, including the *Cypridina* and *Vargula* species, and the midshipman fish. The ostracod luciferase enzymes were later cloned from a *Vargula* species (Haddock et. al. 2010). On a similar track, the first photoprotein, aequorin, was originally discovered, isolated, and characterized from the hydromedusa *Aequorea Victoria* in the 1960's, and later cloned in the 1980's. This species was also the source of the original green fluorescent protein. By the end of the 1980's, scientists had also begun to study the dinoflagellate luciferin. It is very similar to chlorophyll in plants and mainly only differs in the metal ions which are present in the molecule. The two compounds may in fact be interconverted by the dinoflagellates on a day-night cycle as the cell alternates between photosynthesis and luminescence on a circadian basis (Haddock et. al. 2010).

It was nearly the 1990's when scientists first began to experiment with the possibility of inducing luminescence is non-luminescent organisms. In an experiment done by Eric M. Thompson and others in 1988, a northern non-luminescent population of *Porichthys notatus* was given luciferin from other species, in an attempt to induce bioluminescence. They were able to conclude that not only could luciferin from the luminescent southern species of *P. notalus* induce bioluminescence capabilities, but in addition just a small amount of luciferin protein from a species called *Vargula* could as well. Even more striking was the fact that the luminescence could then last undiminished for more than two years, even though the *Vargula* luciferin protein is highly unstable. This fact that more light could be produced in *P.*

notalus than was accounted for by the amount of luciferin administered suggested to them that "…the luciferin protein either recycles [itself] or is synthesized *de novo* in the fish" (Thompson et. al. 1988).

Further discoveries about bioluminescence, including the evolutionary origins of luminescence systems, were not made until the 21st century.

III. More Recent Literature

As in many areas of study within the realm of science, the knowledge of bioluminescence has exploded in the past two decades or so with the advances of modern technology. Scientists soon began to harness bioluminescence as a scientific tool, and just in the past ten years, much more research has been done concerning the possibility of inducing luminescence in various organisms and mass-marketing the products of such procedures.

In 1998, Jean-Francois Rees and others did an experiment titled "The Origins of Marine Bioluminescence: Turning Oxygen Defence Mechanisms into Deep-Sea Communication Tools". They suggest that the original primary function of the coelenterazine enzyme was to detoxify deleterious oxygen derivatives. A functional shift from this antioxidative function to its current light-emitting function might have occurred when the strength of selection for antioxidative defense mechanisms decreased, made possible when marine organisms began to colonize deeper layers of the ocean. In the deeper waters, exposure to oxidative stress would have been considerably reduced due to less light irradiance and lower oxygen levels (Rees 1998).

According to Haddock, bioluminescence has actually evolved independently many times throughout history. Though it is difficult to calculate the exact number of times, Haddock and his colleagues were able to generate a rough estimate by summing the number of distinct light-producing chemical mechanisms across the monophyletic lineages, and guess that bioluminescence has evolved a minimum of 40 times, and likely more than 50, among extant organisms (Haddock et. al. 2010).

To learn more about the origins of bioluminescence capabilities in evolution, Haddock considered two even lineages of ostracod crustaceans, Halocyprida and Myodocopida. These species use two different luciferins, and are thought to have diverged more than 400 million years ago, suggesting that this may be the maximum age for at least one known system of luminescence. Another clue regarding the age of luminescent capabilities comes from the fish order Stomiiformes, which is bioluminescent throughout and thought to have originated during the Cretaceous era, about 100 million years ago (Haddock et. al. 2010).

A significant event regarding bioluminescence occurred in 2001, when the first man-made bioluminescent fish was introduced. According to Guinness World Records, the fish was created in Taiwan by H.J. Tsai, a professor in the department of fisheries science at the National Taiwan University. It was soon sold by the Taipei-based Taikong Corporation. Called the Frankenfish, it was a green-glowing specimen of the popular aquarium species known as the zebra fish. The induced bioluminescence came from the introduction of jellyfish DNA into the fish's DNA. The fish were officially known as TK-1 or night pearls, and were followed by the TK-2 in 2003. The TK-2 generation glowed red rather than green, and had received its bioluminescent gene from a species of red-glowing coral (Guinness World Records 2001).

IV: Conclusion

Bioluminescence is widespread across many forms of marine animals, and has a clear impact on marine ecosystems. Its capabilities have empowered a number of marine species within ecosystems, and shaped behavioral ecology by changing predation techniques, defense mechanisms, and forms of communication.

Our knowledge of bioluminescence has come a long way over the ages – from mere rumors of monsters of the deep to the ability to create man-made luminescent organisms. Nowadays, humans are even employing it in genetic and biomedical research, and exploring new applications such as creating plants that luminesce when they need water (New World Encyclopedia 2008). Some are even using the green fluorescent protein and the luciferin-luciferase system as reporters of gene expression, which subsequently has enabled them to create glowing green bunnies, according to Biron (2003).

Yet much of the details of bioluminescence still remain unknown. Promising areas of research for the future include understanding the biosynthesis of luciferin, expanding our knowledge of the natural functions of luminescence for many marine animals, and demystifying the major luminescence systems which we do not yet understand – including those present in certain echinoderms, polychaetes, and tunicates (Haddock et. al. 2010). As it has for many centuries, this topic may continue to fascinate and baffle humans for several more generations.

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