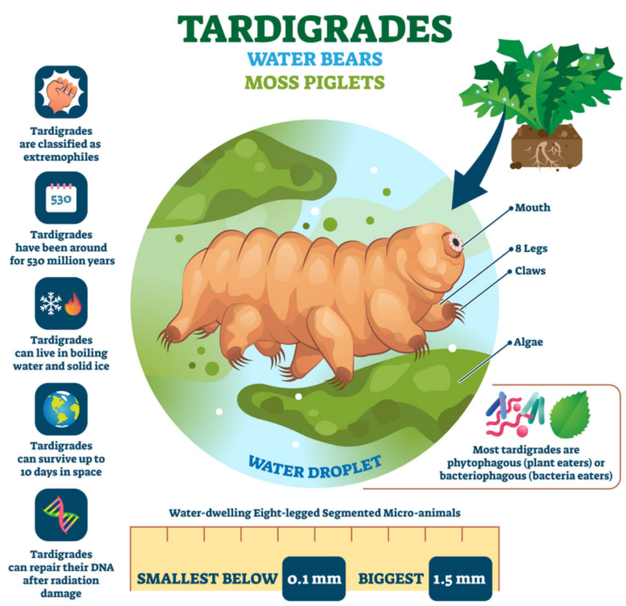
The Tardigrade Chronicles: A Tale of Molecular Superpowers!

Deep in the leaf litter of a forest floor lived a community of peculiar creatures known as tardigrades. Also called water bears or moss piglets, these microscopic animals were nearly invisible to the naked eye. But despite their small stature, the tardigrades were hardy survivors that had roamed the Earth for over half a billion years.



Source: https://www.allthingslistening.com/tardigrades-script.html

Source: https://science.nasa.gov/tardigrade-moss

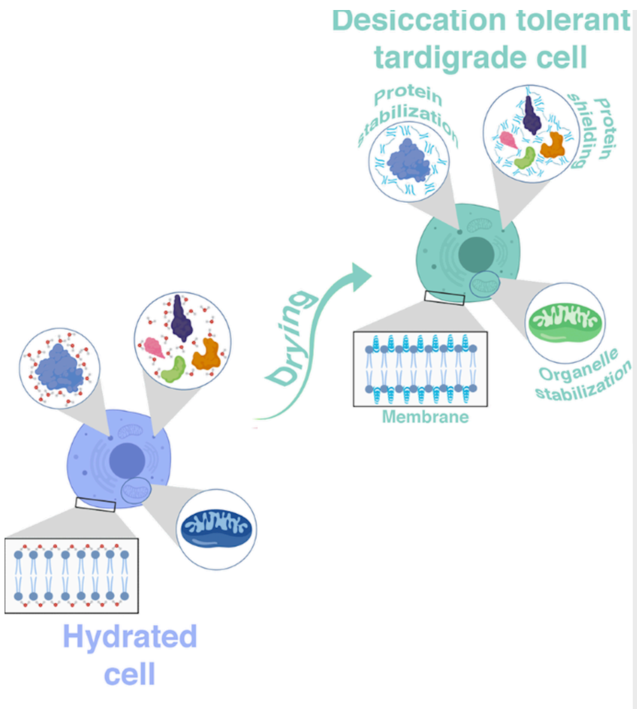
With puffy segmented bodies and four pairs of stubby legs, tardigrades possessed an endearing appearance. They fed primarily on plant matter and other microorganisms found in their habitats, which could range from the depths of the ocean, to the peaks of mountains, to the concrete jungles of urban areas. Yet these were no ordinary cute mites. Tardigrades possessed some astounding adaptations, allowing them to withstand forces that would obliterate most other lifeforms.

On a scorching summer day, the moss in the forest started to dry up due to lack of rain. As their water supply dwindled, the tardigrades' specialised sensor cells signalled the imminent danger. It was time for their survival mechanisms to activate. Curling up into protective balls, the tardigrades focused their energy inward, ready to unleash their extraordinary powers. Soon, their exoskeletons would harden, shielding their vulnerable interiors until the rains came again.

Within the tardigrades' cells, a group of unique molecules known as TDPs (tardigrade-specific intrinsically disordered proteins) prepared for the impending challenge. Their mission was clear: to construct a formidable barrier when the desiccation, or extreme water loss, arose. Accompanying the TDPs, trehalose, a vital disaccharide sugar, played a crucial role in this grand strategy. Trehalose molecules strategically bonded to proteins, membranes, and other cellular components, acting as miniature shields that enveloped and stabilised the delicate contents of the cells.

As the dryness intensified, these remarkable molecules sprang into action, forming a layered defense system. Initially, the loosely arranged TDPs began to interlock, intricately weaving their chaotic domains into an ordered, crisscrossing network. Simultaneously, trehalose reinforcements swiftly moved from one target to another, sealing any gaps and providing additional protection.

Together, the TDP infrastructure and trehalose barriers crafted a microscopic masterpiece. The disorderly proteins adeptly transformed the cellular medium from a liquid state into a solid, glass-like condition. The resilient glass casings safeguarded each cell, while the trehalose shields prevented the organelles within from losing function due to desiccation. This process, known as vitrification, stood as one of the tardigrades' most remarkable superpowers.



Vitrification makes tardigrade cells tolerant to desiccation.
Adapted from source: https://biosignaling.biomedcentral.com/articles/10.1186/s12964-020-00670-2

With their vitreous shelters firmly established, the tardigrades' didn't need as much water to maintain their internal cellular environments. They entered a profound slumber known as anhydrobiosis. Their bodily functions slowed down, conserving energy. Encased within their protective vitrified state, the tardigrades could endure the dry environment like this for extensive periods, patiently awaiting the return of rain.

But their arsenal of abilities did not end there. As chilly nights descended on the forest, many tardigrades packed themselves away in hidden crevices and leftover moss clumps, entering yet another protective state…

Ice-binding proteins (IBPs) allowed tardigrades to absorb water onto their surfaces, skillfully preventing the formation of harmful ice crystals within their cells. These remarkable proteins bound to the ice and altered its growth pattern, preserving the integrity of cellular structures. It was as if the tardigrades possessed a magical power to control the ice, ensuring it formed in a way that posed no harm to them.

Furthermore, their abundant trehalose provided crucial support, preventing cellular structures from fracturing or rupturing due to ice build-up or osmotic imbalances. Thanks to these incredible adaptations, the tardigrades could withstand extreme sub-zero temperatures. These tiny superheroes were built like resilient tanks, equipped to thrive even in the harshest of environments.

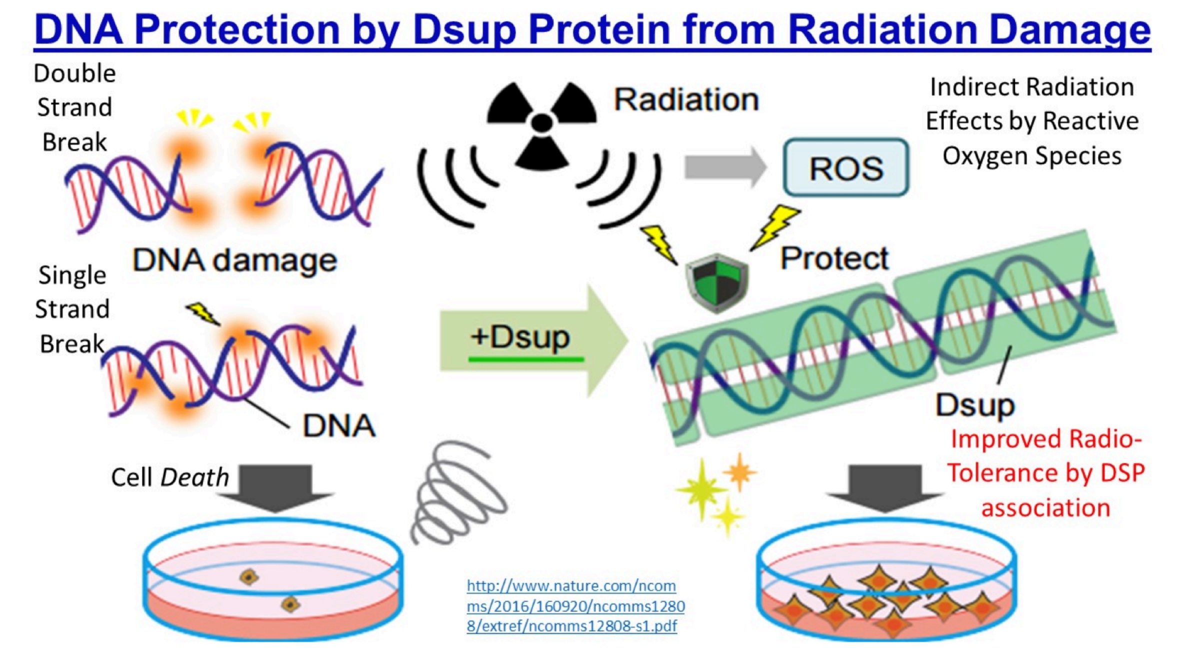
But little did the tardigrades know, they were about to face their biggest challenge yet—a journey beyond the sky, into the great unknown of space. Scientists discovered their extraordinary resilience and became fascinated with sending tardigrades on the first live animal mission to space. In 2007, thousands of the tiny creatures were dried up in anhydrobiosis and loaded into special containers aboard the FOTON-M3 Russian rocket. For 10 days, the tardigrades floated in low-Earth orbit, experiencing temperatures ranging from -15°C to +40°C and the destructive pressures of solar and cosmic radiation.

Tardigrades are so adaptable, they can relax in space!
(Original Art)

To the scientists' amazement, when they were rehydrated back on Earth, over 68% of the space-faring tardigrades revived without any effects of their interstellar voyage. They had proved that not even the vacuum of space could conquer these miniature mighties! One of the most astonishing discoveries was the tardigrades' ability to withstand and repair DNA damage caused by cosmic radiation.

Cosmic radiation consists of high-energy particles that permeate space and can cause harm to living organisms. When the tardigrades were exposed to cosmic radiation, their DNA suffered breaks, which, if left unrepaired, could lead to genetic mutations and cell death.

However, the tardigrades possessed a sophisticated DNA repair mechanism that safeguarded their genetic material. Within their cells, they produced a range of DNA repair enzymes, such as DNA-dependent protein kinase (DNA-PK). This remarkable enzyme played a crucial role in recognizing and repairing double-strand breaks (DSBs) in the DNA. It acted as a molecular surgeon, meticulously mending the damaged strands and ensuring the integrity of the tardigrades' genetic code. Other repair proteins, such as Rad51 and Ku proteins, were also involved in different repair pathways, working together to restore the DNA to its original state. Also, damage suppressor proteins (Dsup) unique to tardigrades shielded their DNA from any more radiation. By specifically recognizing and binding to damaged DNA sites, they could block harmful molecules, preserve DNA integrity, and prevent any further damage.

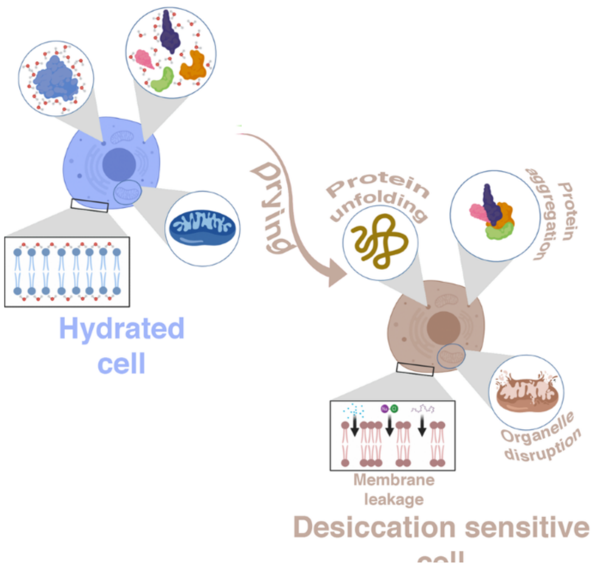


Source: https://dlnp.jinr.ru/images/jevents/5e85c1ec4ca019.87998701.pdf

The scientists were amazed by these findings. The tardigrades' ability to repair DNA damage provided valuable insights into the mechanisms of DNA repair and offered a potential avenue for future applications in biotechnology and medicine. The knowledge gained from tardigrades' DNA repair mechanisms held the potential to protect human cells from radiation-induced harm or enhance DNA repair in various diseases. By studying the molecular pathways involved in tardigrades' adaptations, scientists could someday uncover key proteins or enzymes that could be targeted for radioprotective strategies during cancer treatment or accidental radiation exposure. Similarly, the molecular adaptations observed in tardigrades could inspire the development of biopreservation technologies, improving the long-term storage and transport of living tissue for regenerative medicine and organ transplantation.

The tardigrades have conquered every harsh terrain on Earth and even space itself, and soon they may even help fight human diseases! But there remains one threat they may struggle against, and it may well be our fault: global warming. While tardigrades are champion desiccators and cryoprotectants, temperatures above 40°C start to cause issues for their biochemistry.

At a molecular level, high heat can denature and irreversibly damage the tardigrades' proteins in unique ways that trehalose cannot fully repair. The hydrogen bonds holding protein structures together break down, leaving the proteins in unfolded aggregations that cannot return to their functional shapes. Membranes become leaky and permeable. DNA strands separate and recombine abnormally. If temperatures get too hot, oxidative damage to amino acids and lipids ensues, eventually causing apoptosis (programmed cell death), or necrosis (breakdown due to extensive damage) in the cells.



High temperatures can damage cells and prevent tardigrades from attaining desiccation tolerance
Adapted from source: https://biosignaling.biomedcentral.com/articles/10.1186/s12964-020-00670-2

While some studies show that certain heat-adapted tardigrade species can withstand brief 50°C bursts due to heat shock proteins, extended heat waves may prove deadly. As climate change raises global average temperatures beyond what life on Earth has experienced for millions of years, many environments are forecast to reach hazardous levels that exceed the tardigrades' thermal limits on a regular basis. The poor tardigrades' highly sensitive environments like forests and moss beds are also predicted to dry out permanently in some parts of the world.

If tardigrade populations take a nosedive, it could disrupt entire ecosystems that rely on their critical role as decomposers and microbial consumers. From an anthropic point of view, that also means losing out on the biomedical potential they represent.

As the threat of global warming now looms over us, tardigrades face their greatest challenge yet. The rising temperatures and prolonged heatwaves will push their resilience to the limits. The once-safe havens of forests and moss beds will begin to wither and dry. So while these tiny titans have triumphed over nature's toughest trials for over 500 million years—their resilience is not limitless. Even superhero tardigrades may struggle to withstand climate change without human intervention to curb it. Their story serves as an important reminder that we must preserve biodiversity and protect the intricate balance of life on Earth—for the sake of all species, including our own. So the next time you come across a seemingly inconspicuous patch of moss in your backyard, take a moment to reflect on the hidden wonders within. Think of the valuable lessons they can still teach us, if only we give them a fighting chance.

Further Reading:

- https://dlnp.jinr.ru/images/jevents/5e85c1ec4ca019.87998701.pdf
- https://www.ucl.ac.uk/biosciences/home/study/partnerships-and-innovation/outreach-and-public-engagement/projects/ucl-young-bioscientist/tardigrades
- https://biosignaling.biomedcentral.com/articles/10.1186/s12964-020-00670-2
- https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/Tiny_animals_survive_exposure_to_space