On the lives of stars and cells

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Although the important characteristics of life are metabolism, reproduction and evolution through interaction with the environment, life can also be summed up as the ultimate cosmological consequence of forces of nature acting in hierarchical sequence, the forces binding the quarks to form protons and neutrons, then atomic nuclei, then atoms, and finally the electromagnetic force becomes dominant in forming molecules. Since these forces are prevalent across the universe, the definition of life does not apply to the biological system alone, but also to systems that involve entirely physical processes. It is therefore not surprising that stars mimic living cells in terms of having a life cycle, although this life deviates from the classic definition of 'biological life'. This note attempts to reinforce the concept that stars like cells do not live forever and for both there is a time to live and a time to die. While being able to follow real-time cosmic evolution through the eyes of Hubble is truly unique, it is also equally fascinating to observe cell birth and death through the microscope. What is more interesting is the existence of striking resemblance between the two life processes – one micron-sized and the other, millions of miles sized.

Stars – a compact body of plasma in the outer space, held together by their own gravity and sufficiently massive to sustain nuclear fusion – can exist in loose stellar association with only a few stars or as enormous globular clusters with hundreds of thousands of stars[1]. Globular clusters are tightly bound by gravity which gives them their spherical shapes and relatively high stellar densities toward their centres. Similar aggregates are prevalent in the biological world as 'neurospheres' – which are free-floating, spherical aggregates of neural stem cells that can proliferate in culture and appear like compact globular clusters consisting of few to thousands of cells[2].

Figure 1 *a* shows the globular cluster M2 which has a diameter of about 175 light-years and contains about 150,000 stars. It is one of the richer and more compact globular clusters. A neurosphere isolated from rat subventricular zone[2] (which is the home to neural stem cells having the ability to differentiate into different cell types of the brain) is shown in Figure 1 *b*. Almost everything about a star including its destiny and fate, as well as its essential characteristics, such as lifespan, luminosity, and size are determined by its initial mass. Stars spend about 90% of their lifetime fusing hydrogen to produce helium in high-temperature and high-pressure reactions near the core. Almost all small and medium-size stars will end up as white dwarfs, after nearly all the hydrogen they contain has been fused into helium[3]. The Hubble Space Telescope (HST) has made it possible to see the details of these processes. Near the end of its nuclear burning stage, such a star goes through a red giant phase and then expels most of its outer material creating planetary nebulae (Figure 1 *c*, *e*, *g*, *i*) until only the hot core remains, which then settles down to become a young white dwarf that shines from residual heat. Planetary nebulae can be considered at the end stage of stellar evolution. Eventually, over hundreds of billions of years, white dwarfs cool to temperatures at which they are no longer visible[4]. A planetary nebula is formed when a fast stellar wind that comes from the central star catches up a slower wind produced earlier when the star ejected most of its outer layers. At the boundary between the two winds, a shock occurs that produces the visible dense shell, characteristic of planetary nebulae. HST images have revealed many

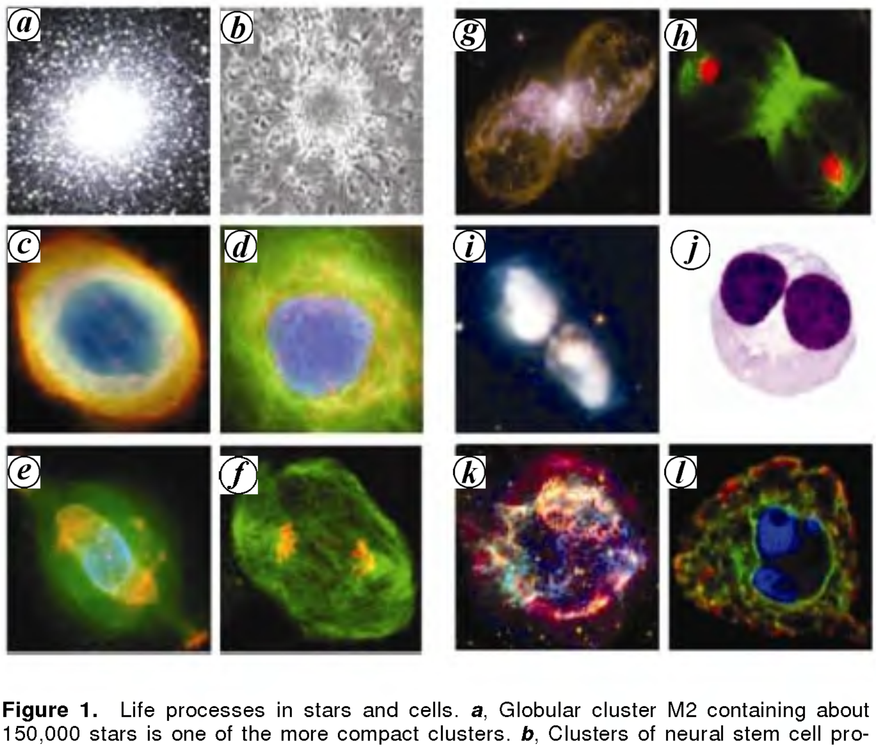

Figure 1. Life processes in stars and cells. ***a***, Globular cluster M2 containing about 150,000 stars is one of the more compact clusters. ***b***, Clusters of neural stem cell progenitor growing as free-floating aggregates as 'neurospheres' (pers. obs.). ***c***, ***e***, ***g***, ***i***, In the last stages of the lives of stars, they wrap themselves in a cocoon of dust. Planetary nebulae emerge from these 'embryos' called proto-planetary nebulae as observed by HST. Ring nebulae M57 (***c***), planetary nebulae NGC 7009 or 'Saturn nebula' consists of two opposing gas jets (***e***), Butterfly or bipolar nebulae Hubble 5 (***g***), and Silkworm nebula IRAS 17441-2411 (***i***). ***d***, ***f***, ***h***, ***j***. Cells at different stages of cell cycle. Bovine pulmonary artery endothelial cell showing Tubulin (green), mitochondria (red) and the nucleus (blue) (***d***; adapted from Molecular Probes, Oregon, USA). Anaphase (***f***) and telophase (***h***) in *Drosophila* showing the chromosomes (red) and microtubules (green). A binucleated cell in which cytokinesis has been blocked (***j***; pers. obs.). ***k***, ***l***, Death of star and cell. Stars explode in Cassiopeia supernovae (***k***). A cell undergoing apoptosis (***l***).

planetary nebulae to have extremely complex and varied morphologies. The mechanisms which produce such a wide variety of shapes and features are not yet well understood, but binary central stars, stellar winds and magnetic fields may all play a role. Importantly, metallicity can influence the duration that a star will burn its fuel, control the formation of magnetic fields and modify the strength of the stellar wind[5]. The observed shapes of planetary nebulae are puzzling: most of them are bipolar or elliptical (Figure 1 *e*, *g*, *i*), rather than spherically symmetric (Figure 1 *c*).

Because most of the gas in a typical planetary nebula is ionized, the effects of magnetic fields can be significant, giving rise to phenomena such as filamentation and plasma instabilities (Figure 1 *e* and *g*). Hubble 5 is an example of 'butterfly' or bipolar nebula, with the heat generated by fast winds causing each of the lobes to expand (Figure 1 *g*). The HST images of Hubble 5 reveal the presence of filamentary structures in the core regions, which correspond to collimate flows in various directions. The lobes also show disorganized filamentary structures and complex ionization patterns. By fitting the observed spectral energy distribution and the V-band image of proto-planetary nebula IRAS 17441-2411 or the 'Silkworm nebula' by a two-dimensional radiation transfer model, HST has shown that the two lobes are separated by a dust lane or circumstellar disk[6] (Figure 1 *i*). Besides wrapping themselves in a cocoon of dust from where planetary nebulae emerge during the last stages of their lives, stars can die and explode as supernovae[3,4] in a near-perfect spherical manner as observed in Cassiopeia A (Figure 1 *k*). In other words, planetary nebulae and supernova play a crucial role in the ecology of the galaxy, returning to the interstellar medium, heavy elements and other products of nucleosynthesis (such as carbon, nitrogen, oxygen and calcium), that are crucial for the survival of the biological unit of life – 'the cell'.

Cell – the minimal self-reproducing unit and vehicle of transmission of genetic information – reproduces by duplicating its contents and dividing into two. Cell reproduction begins with duplication of the cell contents, followed by distribution of those contents into two daughter cells. This cycle of duplication and division (cell cycle) consists of nuclear division (mitosis) followed by cytoplasmic division (cytokinesis)[7]. Chromosome (structures containing hereditary information) duplication occurs during the synthesis (S) phase of the cell cycle, whereas other cell components are duplicated continuously throughout the cycle. During the mitosis phase, the replicated chromosomes are segregated into individual nuclei. The mitotic phase can be further divided into prophase, prometaphase, metaphase, anaphase and telophase, which occur in strict sequential order[7]. Cell-cycle organizations have been highly conserved throughout evolution and studies in a wide range of systems have led to a unified view of eukaryotic cell-cycle control. The assembly and disassembly of microtubules (cytoskeletal machinery of the cells) and the force generated in the process plays a critical role in separating daughter chromosomes during mitosis[7]. The distribution of chromosomes (red) and microtubules (green) in the fruit fly *Drosophila* during the anaphase stage (Figure 1 *f*) has striking similarity to the planetary nebula NGC 7009 that has a bright central star at the centre of a dark cavity bounded by a rim of dense, blue and red gas (Figure 1 *e*). The cavity and its rim are trapped inside a smoothly distributed greenish material in the shape of a barrel and comprise of the former outer layers of the stars. Lying along the long axis of the nebula is a pair of red 'ansae' (or handles consisting of clouds of low-density gas). Each ansa is joined to the tips of the cavity by a long greenish jet of material (Figure 1 *e*). The final stage of mitosis (telophase) where the daughter chromosomes appear at the poles of the spindle microtubules (Figure 1 *h*) bears resemblance to the filamentary structures observed in the core region of butterfly nebulae Hubble 5 (Figure 1 *g*). Figure 1 *f* and *h* shows chromosomes (red) and microtubules (green) during anaphase (*f*) and telophase (*h*) in *Drosophila*. A binucleated cell in which cytokinesis has been blocked (Figure 1 *j*) appears like a bipolar planetary nebula. If life begins at conception, then death begins at birth. In multicellular organisms, cells that are no longer needed or pose as threats to the organism are induced to commit suicide. The pattern of events in death by suicide is so orderly that the process is often called programmed cell death (PCD) or apoptosis[7]. Apoptosis involves membrane changes, shrinkage of cytoplasm, fragmentation of DNA, and cell death (Figure 1 *l*). This order pattern of PCD in a way is comparable to a star going from a red giant phase through planetary nebulae to become a white dwarf.

Today's technology has made the very large and very distant small enough and close for us to study and understand. With the interdisciplinary science of astrobiology seeking to answer fundamental questions on the origin, evolution, distribution and destiny of life, wherever it might exist in the universe, future investigations into these questions are promising as this emerging field develops a more coherent picture of the conditions and processes occurring on the early universe. While newer discoveries will undoubtedly lift the mysteries surrounding the origin of life, they will be unable to diminish the marvel of how intricately organized chemical factories in the universe (the cell and the star, for example) possess constancy in fundamental mechanisms (having a life cycle by their own standards), despite having individual particulars.

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