Astrobiology: a new science for a new century

In Search of Alien Life

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Ewa Szuszkiewicz and Franco Ferrari pursue and coordinate interdisciplinary basic research in astrobiology, with a firm eye out for applications and implementations that will improve the conditions of life on earth

There can be no greater challenge for modern science than the discovery of how life began on Earth and whether suitable conditions for the existence and development of life may be found across the Universe

NASA, recognizing astrobiology as one of the key emergent sciences of the 21st century, has committed significant resources to develop a national infrastructure for astrobiology in the US. The European Space Agency (ESA) has established itself as a world leading scientific organization with an exciting and innovative astrobiology program. The outstanding success of Mars Express, the dramatic landing of the Huygens probe on Titan in January 2005 and the ongoing success of the Cassini-Huygens Mission to Saturn have demonstrated humans' ability and innovation in space technology. The launch of the Rosetta mission to study and land upon a comet, Europe's major investment in the European Southern Observatory (ESO) through use of the Very Large Telescope (VLT) and the approaching the employment of the Atacama Large Millimeter Array (ALMA) as well as the development of the Darwin Space Telescope array to search for life-supporting exoplanets indicate the breadth and innovation of the scientific community. The ExoMars mission to send a rover to Mars in 2011 to search for evidence of biological activity and the development of the European Aurora Science program have the opportunity to inspire young people to pursue careers in science and technology.

The Polish answer to the call of astrobiology and to the formation of several national astrobiology centers all over the world is the CASA* (Centre for Advanced Studies in Astrobiology and Related Topics) with its headquarters in Szczecin.

The enigmatic smile of astrobiology

The marriage between astro- and biosciences in astrobiology is well symbolized by Figure 2, which shows two fundamental diagrams: first, the H-R (Hertzsprung-Russell) diagram which plays a major role in stellar evolution, and second, the phylogenetic tree built on the genetic information obtained from ribosomal RNA and comparisons between different organisms. These are just two elements in the whole picture, but their significance for astrobiology is of the same caliber as that of Mona Lisa's smile for the Leonardo da Vinci painting.

Stellar evolution takes place on timescales much longer than human lifetimes or even the recorded history of civilization. For this reason, we cannot watch a single star hoping to learn how it evolves, but we may use the fact that there are many stars in the sky, in different stages of their life cycle. In the H-R diagram, stars are classified according to the relationship between their temperature and luminosity, into several distinctive groups along well-defined sequences. In tandem with the laws of physics, the H-R diagram provides a way to understand how stars evolve with time.

The second diagram of Figure 2 plays the same role as the H-R diagram in our efforts to trace back the evolutionary history of life on Earth. There is no way to know what the first organisms looked like by direct observation. A record of the appearance of life on Earth and its early evolution should be preserved in rocks dating from the earliest epochs - but there are unfortunately no rocks dating from the first 500 million years of the Earth's his-

NASA

Figure 1.
Where in the cosmos might we find life? Before we begin to look on planets circling other stars, new missions will set forth to study the possibly favorable conditions for life on the moons of the Sun's two giant planets: Jupiter and Saturn

tory because they have been destroyed by plate tectonics and other thermal processes. Nonetheless, there are living organisms on the Earth which appear to be at different stages of evolution, exactly like the stars in the sky. The phylogenetic tree shows the relation between different organisms based on ribosomal RNA data. Species closest to the center of the tree should be nearest to our last common ancestor. The phylogenetic tree, combined with the laws of physics and chemistry, which for certain constrained the evolution of the most primitive organisms, should give us a hint of the earliest stages of evolution after life started around 3.85 Ga ago. Today, for the first time in human history, there is a chance to solve this problem.

Let us have a look how astrobiological studies are carried out at Poland's CASA* astrobiology centre, one of the European centers co-ordinated by the EANA (European Astrobiology Network Association) and led by the authors of this article. Seeing as the search for both ancient life forms and for water in the Solar System have already been described in previous issues of *Academia*, we would like to give a brief overview of the astrophysical and physical aspects of this research, which are our main scientific areas of expertise.

Polymers

Life can be understood as a chemical system, in which biopolymers like proteins, carbohydrates, as well as DNA and RNA play a central role. This is the reason why one of the authors of this article, Franco Ferrari, working on polymer physics for a decade, grew interested in astrobiology. Polymers are materials with truly fascinating properties. There is a certain toy made of polymers which looks like a solid body. However, after putting it into a glass and waiting about half an hour, one discovers that it has adapted its shape to the contour of the glass filling it completely, exactly like water would have done. Indeed, the toy is a liquid. The extremely high value of its viscosity, which makes its molecules move

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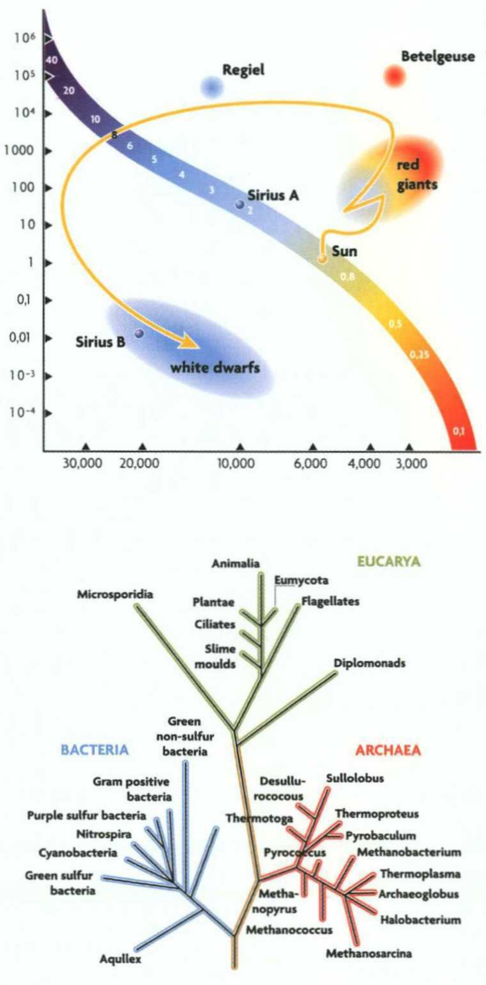
so slowly in comparison to those of water, is achieved because polymers consist of long molecular chains. Usually the chains are entangled together in so complicated a way that their motion is necessarily slow and the viscosity of the material grows enormous. Up to now, the most striking progress toward an understanding of the phenomena connected to entanglement has been obtained in the case of polymer rings. The ring configuration is not so uncommon in nature; many viruses and bacteria find it convenient to shape their DNA in rings. In industrial applications, as well, the formation of rings is used to create polymer materials with the desired properties. A set of entangled polymer rings cannot disentangle like open chains do, so that its topological configuration cannot change in time. It is convenient to imagine polymer rings as small circuits, in which ghostly currents circulate and create ghostly magnetic fields. Out of these magnetic fields one may build an infinite number of mathematical quantities, but only a few of them will remain constant if one deforms the circuits in an arbitrary way without breaking their lines. Such quantities are called topological invariants and are exactly what is needed to describe the topology of a system of polymer rings. Luckily, there is a theory, called the Chern-Simons field theory, which constructs topological invariants for us, so that we do not need to put much effort in this task. The first model of polymer systems based on Chern-Simons field theories, developed by Franco Ferrari et al. in 1998, to date remains the most sophisticated model describing the statistical mechanics of polymer rings. Most importantly, this model provides testable predictions. For example, it tells us that two polymer rings are reciprocally attracted just because they are entangled. Such attractive forces have in fact been observed in the DNA



Wawrzyniec Święcicki

Figure 2. **Two fundamental diagrams representative of research in astrobiology. Above: the H-R diagram shows stars in different stages of their evolution; the curve shows the evolutionary path of the Sun. Below: the phylogenetic tree illustrates genetic similarities between different species, telling a story about the possible history of their evolution. The longer the branch between two organisms, the greater the difference in ribosomal RNA sequences**

of bacteria in a famous experiment by Levene et al. in 1995. Yet there are also numerical simulations which show that if polymer rings are just weakly entangled, then they will in fact repel themselves. For this reason, when the Chern-Simons model was presented in 2000 at a seminar at MIT in Boston, M. Kardar, one of the world's leading scientists working on the subject, claimed that there was something wrong in the model, because it predicted just attraction, but not repulsion. The resulting discussion ended favorably, but it took three years and a very sophisticated mathematical tool, called the Bogomol'nyi transformation, to show that the model is indeed also in agreement with the numerical simulations. There is no space here to discuss how all this is related to astrobiology and to the evolution of species - suffice it to mention that the knowledge that proteins and DNA are polymers forming rings and loops and are subject to the laws of physics has inspired E. Trifonov to formulate a suggestive hypothesis on the DNA of primordial organisms, which we are currently checking using calorimetric techniques.

In search of life-friendly environments

The confirmed existence of exoplanets around stars other than our own Sun has been one of the most exciting advances of modern astronomy. At present we still do not know whether the existence of rocky planets is common or very rare around sun-like stars and we therefore do not know if potentially life-sustaining planets are plentiful, exceedingly few or altogether absent. This will change soon - in the fall of 2006, with the launch of the COROT mission, which will add many lower mass planets, if they are there around other stars, to the list of numerous Jupiter-like exoplanets known today. Moreover, the technique of gravitational microlensing, introduced by Bohdan Paczyński and used in ground based observations, could at any moment reveal the existence of Earth-mass rocky planets, where conditions might be favorable for the development of life. Investigating how habitable planets form requires an understanding of the architecture of planetary systems (planet masses and distances from their stars). Aside from observations, one of the main methodologies here is to model the evolution of planetary systems by means of advanced numerical calculations - a type of research pursued by one

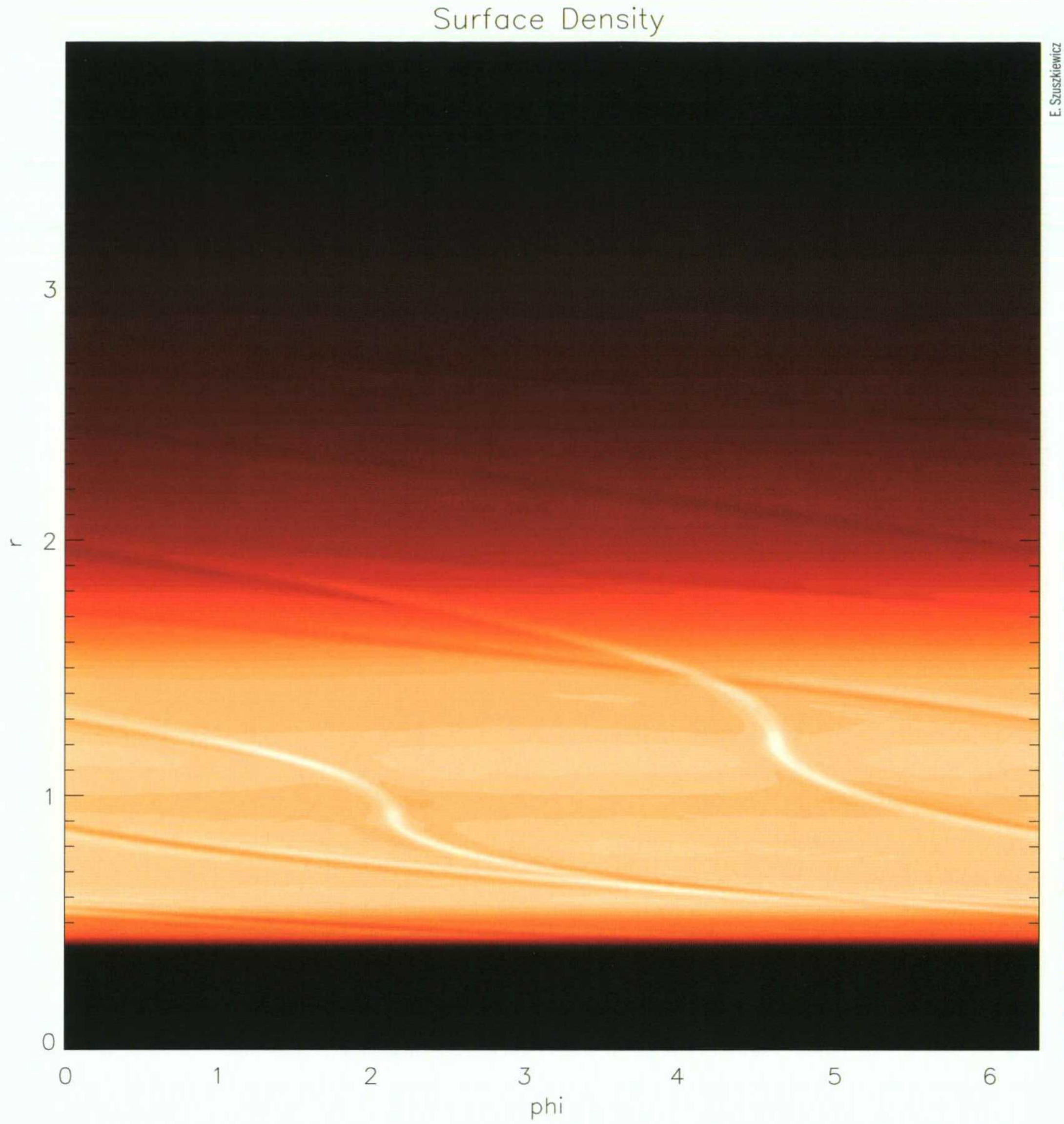


Figure 3.
The two largest mass planets orbiting the pulsar PSR B1257+12 embedded in a gaseous disc formed from material left after a supernova explosion. The ratio of their orbital periods is close to 3:2 The planets are represented by bright spots. The characteristic wakes produced by planets are apparent. The disc is coloured according to density: the brighter part is the denser region of the disc

of the authors of this article (E. Szuszkiewicz). Planet formation is tightly connected to star formation and stellar evolution. One should be able to learn how planetary systems evolve, using an approach similar to that applied to stars. We have detected many planets around the main sequence stars, a few orbiting red giants, and one circling a white dwarf, which means that planets might exist along the whole evolutionary sequence for solar type stars. This comes as good news for the Solar System, because it stands a chance of surviving during the further evolution of our Sun. We also know of two planetary systems around neutron stars, the final stage of the evolution of massive stars. Neutron stars form in supernova explosions. Does this mean that a planetary system can also survive one of the biggest catastrophes in the life cycle of a star? The answer is still not clear, but the most plausible scenario is that such planets form from the material spread around in the supernova explosion. Assuming this scenario and using advanced numerical simulations, E. Szuszkiewicz together with John Papaloizou successfully explained why the two largest mass planets orbiting the millisecond radio pulsar PSR B1257+12, a system discovered by Aleksander Wolszczan, are close to a 3: 2 orbital resonance. Similar studies have the potential to be a powerful tool in our search for Earth-like planets in other systems. The idea behind the H-R diagram is also being used to understand the early epoch of planet formation, observing and modeling circumstellar, protoplanetary and debris discs, in an effort to reproduce the evolutionary sequence of events before the planets were born.

Research in astrobiology goes on, trying to improve our understanding and appreciation of our own place in the Universe. The saga continues. ■

Further reading:

Ferrari F., Szuszkiewicz E. (Eds.). (2006). *Astrobiology: through cosmic dust to DNA* [in Polish]. Szczecin: Szczecin University Press.

Papaloizou J.C.B., Szuszkiewicz E. (2005). On the migration-induced resonances in a system of two planets with masses in the Earth mass range. *MNRAS, 363*, 153-176.