Prof. dr hab. Marek Sarna

ORCID: **0000-0003-4745-3923**

E-mail: **sarna@camk.edu.pl**

From Copernicus to ESO, How do Today's Astronomers Observe the Universe?

Abstract

Astronomical techniques of observation have come a long way from the times of Copernicus to modernity. For Nicolaus Copernicus as well as his contemporaries, and later Galileo as well as Hevelius, the basic optical instrument and detector was the eye. Today, we build ever larger telescopes, develop very precise registration techniques, and establish databases gathering terabytes of information about the Universe which surrounds us. We reach out through our observations towards the Solar System and further, through the centre of our Galaxy to the farthest edges of the Universe. The fundamental question remains, however: wherefrom and how did we come to be in this world, and do we understand it?

Copernicus and His Instruments

It may surprise many that in the times of Copernicus a scholar never parted with their "analyser" and optical instrument. Indeed, their mind – fostered by the Medieval university – was well-trained in analysis by the trivium and quadrivium; their instrument, unchanged since the era of Ptolemy, was the eye.

Their mind was aided by knowledge as well as logic, and was immersed in the era's rigors of scientific work and the Aristotelian model of the Universe.

The instruments – Copernicus's instruments – were prostheses which assisted the eye and the mind. It needs be realized that Copernicus was an expert in a specific field – mathematical astronomy. The main motive of his work as astronomer was correcting and simplifying Ptolemy's numerical tables, used in determining the arrangement of planets.

What instruments did Copernicus use to achieve this? They were, in fact, simple and hand-made; used mainly in angular measurements. They were not at all atypical of the period; copied from Ptolemy's Almagest. Copernicus describes them in On Revolutions of the Heavenly Spheres. They were the quadrant, the astrolabe, and the parallactic triangle (or triquetrum). Supplementing the set was the solar clock. Let us summarize them.

The Quadrant

A rectangular plate inscribed with an angular scale, its use was in measuring the level of heavenly bodies relative to the horizon. The instrument had to be carefully placed along the plane of the local meridian, and strictly along the plane of the horizon. With the use of the quadrant, an astronomer – such as Copernicus – could determine the latitude at the point of observation – e.g., the town of Frombork. (Fig. 1)

Fig. 1. Solar Quadrant: used for measuring the level of the Sun and the inclination of the ecliptic – Earth's orbit – to the celestial equator.

The Parallactic Triangle (or Triquetrum)

The instrument was used by Copernicus to determine the parallax of the Moon – that is, to measure the satellite's distance from the Earth. It consists of three strips of pinewood screwed together to form an isosceles triangle. Placed on the first strip are two metal viewports, on the second – the scale; the third, along which the others are able to move, is attached to a wooden pole by hinges, which allow the strips to rotate around said pole. (Fig. 2)

Fig. 2. Parallactic ruler or Triquetrum: An instrument used to measure the altitude of Sun (the apparent change in its position resulting from the movement of the observer staying on Earth)

The Astrolabe

Also known as the armillary sphere, it is the most complex of Copernicus's instruments of observation. It was used to determine the Moon's and the planets' position in the sky (that is, their angular height). The instruments is composed of concentric wooden rings, bearing angular scales and viewports. The outermost ring is meant to be fixed, placed on a pole along the meridian. The others represent the ecliptic, the equator, the hour circle, and the meridians. With this instruments, it is possible to determine the ecliptic longitude and latitude of the observed celestial object. (Fig. 3)

Fig. 3. Spherical astrolabe: the most sophisticated ancient astronomic instrument used to determine ecliptic or equatorial coordinates of celestial bodies

What does the Copernican Universe Look Like?

In the times of Copernicus, the dominant canons were three: Aristotelian – of natural philosophy, Euclidian – of geometry, and Biblical. The movements of the heavenly bodies ought be perfect, circular (without beginning nor end), neither accelerating nor slowing down. As the centre of creation, the Earth need be the centre of its rotation. Copernicus did not seek to challenge theological truth claims, even as he moved the centre of the Universe from the Sun to the Earth. He described Earth and all the planets as travelling around the Sun along circular orbits. With this premise, the description of planetary motion was simplified. Yet, to make his assumption function, he did not reject the concepts of deferents and epicycles. (Fig. 4)

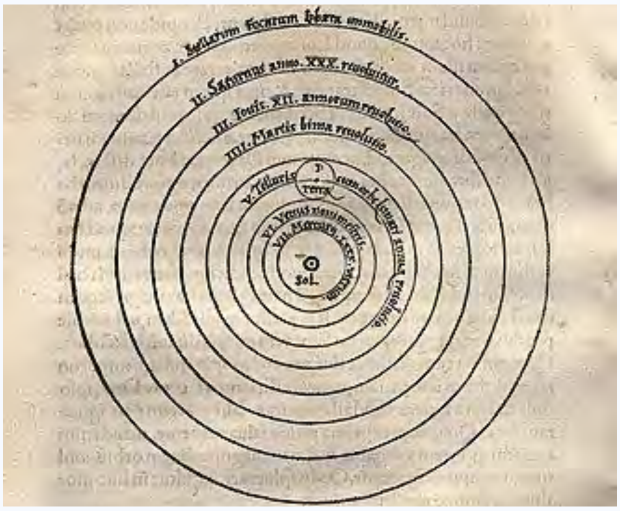

Fig. 4. Heliocentric model from Nicolaus Copernicus De revolutionibus orbium coelestium

Who Follows Copernicus into the Present?

The 17th century brought with it many new technologies, such as the telescope. With it, Galileo first viewed Lunar mountains, observed the phases of Venus (thereby proving that the planet orbits the Sun rather than Earth), discovered the four largest Jovian moons, and saw that the Milky Way is, in fact, an assemblage of stars. The period is marked a breakthrough in the way humanity views the firmament. The next milestone has been laid by Kepler's proposal that the planets follow their paths elliptically, with inconstant speed. Kepler based the proof of his claim on the motion of Mars as observed by Tycho Brahe. Furthermore, Isaac Newton, by formulating his law of universal gravitation, anchored said planetary motions to the Sun.

Copernicus's heliocentric theory overthrew the previous paradigm and established one anew: **The location of Earth is in no way distinguished – the Copernican Revolution is accomplished.**

The Contemporary Paradigm and Methods of Verification

The eye and the mind continue to be foundational. In this aspect, not much has changed, although today the analysing mind is aided by digital computers, and serving as our eyes' prostheses are the instruments of contemporary astronomy, such as those available at the European Southern Observatory – ESO.

Gone is the barrier of the fixed stars; the Universe expands dangerously; the limit to the transfer of information is the speed of light; nebulas birth galaxies and quasars. Contemporary cosmology gave us the Big Bang and relic radiation as proof, but also generated new problems: initial instability, as well as dark matter and energy. As such, the development of new techniques and technologies proved indispensable.

Tasting the Universe

Returning to the basic human observational instrument – namely, the eye – it is worth noting that the range in which it registers electromagnetic radiation is extremely limited. It is the so called optical spectrum – all the colours of the rainbow. Stretching in both directions is radiation of the gamma, Roentgen, and ultraviolet types, as well as the far infrared spectrum, microwaves, and radio waves. Here we cannot manage without some form of prosthesis. The times of Herschel and Hevelius – when an observer themself constructed and used a telescope or spyglass – are long gone. In the 19th and 20th centuries humanity began to combine their efforts, and new, university-funded observatories began emerging. At times, with the rising costs of increasingly more complicated apparatus, consortia of diverse scientific and technical institutions were formed. It was also realized very quickly that said apparatus should not be placed on Earth's surface alone – that breaking away into space outside the planet's atmosphere is needed. Two kinds of organization were created: the European Southern Observatory (ESO) –the main observational instruments of which are located in the Chilean Andes – and the European Space Agency (ESA) – which is engaged in the construction and usage of orbital satellites. Poland is a full member of both these organizations, and makes use of the entirety of their scientific infrastructure.

In the present overview we will concentrate only on ESO, which Poland joined in the year 2015. The headquarters of the institution are located in the German municipality of Garching bei

München (that is, near Munich), and its full name is the European Organisation for Astronomical Research in the Southern Hemisphere. Garching is the scientific, technical, and administrative centre of ESO, but the organization has another office in Santiago de Chile – most of its observational instruments are located in the Andes. (Fig. 5) ESO owns three currently functional observatories, whereas one is under construction in the Atacama Desert, in Chile. These four locations are:

1. the La Silla Observatory (possessing both 2.2- and 3.6-meter telescopes, as well as the 3.58-meter New Technology Telescope);
2. the Paranal Observatory (with 2.5- and 4-meter telescopes, plus the Very Large Telescope Interferometer – the VLTI);
3. the Atacama Large Millimeter Array – the ALMA (consisting of a suite of radio telescopes);
4. the Extremely Large Telescope – the ELT – which is under construction, and will become the largest optical/infrared telescope in the world.

The primary mission of ESO lies in creating the European Research Area for astronomy and astrophysics. Each year, a large number of Polish astronomers conducts research utilizing data gathered by ESO observatories. Teams of astronomers are often international, and the results – published in scientific articles. In comparison to the workflow of centuries past, it is clear that scientific work of today is a team effort. Conversely, Copernicus worked alone and had but one student, named Redyk.

Fig. 5. The image of the Paranal platform. The four Unit Telescopes are ready to start the observations. (Credit: ESO/H.H.Heyer)

The efforts of the many experts working at ESO contributed to the rapid development of modern observational techniques such as:

1. **Active Optics:** a technique used in cutting-edge telescopes, conducted by correcting the shape of a thin mirror – in real time – during observations.
2. **Adaptive Optics:** the correcting of image sharpness. The larger the mirror, the more photons it gathers. However, even for observatories of the best quality from the point of view of astronomy, it is not possible to achieve – in the visible spectrum – image sharpness better that that achievable with a 20–30 cm telescope. This is because of the motions of the atmosphere, that is, atmospheric turbulences. Adaptive optics corrects for these motions.
3. **Optical and Microwave Interferometry:** by combining light registered by two or more telescopes, a very precise – separated – image is achieved, which would be impossible with the use of just one such instrument. ESO is a pioneer of this technology, and has implemented it into the VLTI, at the Paranal Observatory.

It is using these observational techniques and ESO telescopes, that many crucial discoveries have been made in the recent decades:

- **Protoplanetary discs.** Pierre Simon de Laplace, near the end of the 18th century, proposed that the Solar System emerged from a swirling, spherical cloud of gas, which, due to gravity, was to be collapsing from the inside and, according to the law of conservation of momentum, swirl increasingly rapidly, so that it flattened along the axis of its rotation. At its centre, most of the cloud was to form a central star, and around it spinning rings of matter were to remain. From said rings – in a similar manner, though on a much smaller scale – were to form planets and their moons. Observation of both the Hubble Space Telescope and the telescopes of ALMA demonstrated this to be the case by discovering the object know as HL Tau – at 180 AU (astronomical units) in size, located at a distance of 140 pc (parsecs) from Earth. (Fig. 6 – HL Tau)

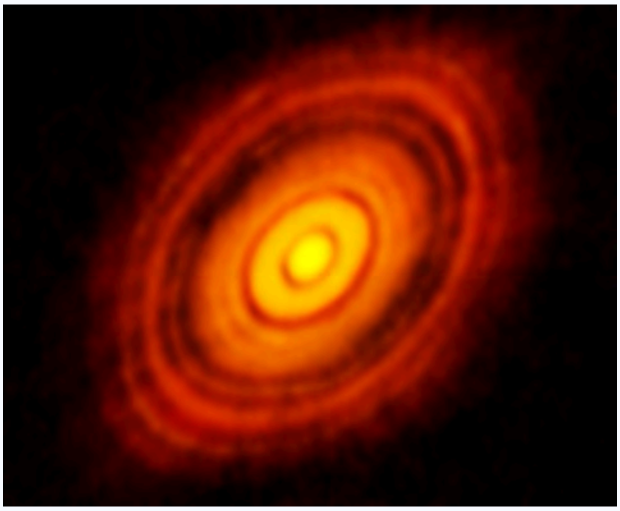

Fig. 6. ALMA image of the **protoplanetary disc** around HL Tauri (Credit: ALMA (ESO/NAOJ/NRAO))

- **Extrasolar planets and planetary systems.** The next great success of astronomy, shattering the notion that our star system stands alone, was the discovery of extrasolar planets. The first such objects – around the pulsar PSR 1257+12 – were discovered, in the 1992, by Polish astronomer Aleksande Wolszczan. In 1995, the first extrasolar planet around a main-sequence star – 51 Pegasi – was found. The discovery of this exoplanet was made by two Swiss astronomers: Michel Mayor and Didier Queloz, who, in 2019, received the Nobel Prize in Physics. Both are members of the Nicolaus Copernicus Academy. Currently, according to NASA reports, over 5000 extrasolar planets – and over 880 stars with more than one planet – are known.

- **The black hole at the centre of our galaxy.** We can call our own the spiral galaxy at the edges of which the Solar System is located. It is a collection of billions of stars of various ages and masses which forms a flattened disk. Found within its inner section, amidst a swarm of stars and dust, is the central supermassive object designated as Sgr A*. Thanks to the telescopes of ESO containing active and adaptive optics, the proper motion more than 6000 stars in a 1 pc radius has been investigated. With the use of Kepler's laws, based on the motion of the 28 best-researched stars travelling across the central section, the mass of the central black hole has been measured as 4.31±0.06 million solar masses. (Fig. 7)

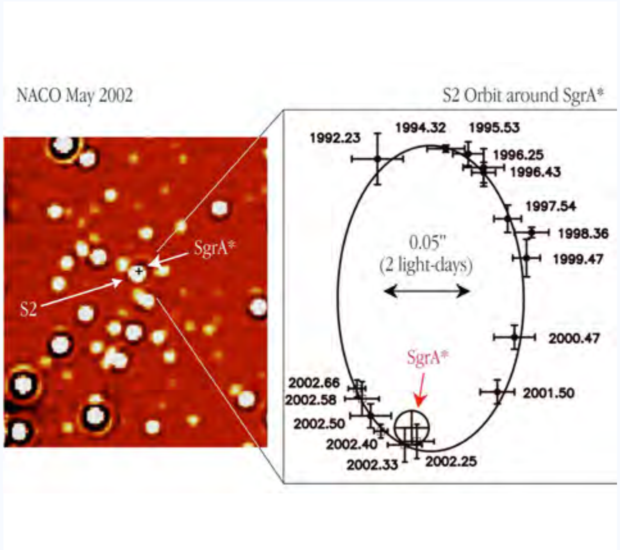

Fig. 7. The motion of a star around **Sgr A*** – the central black hole in the Milky Way (Credit: ESO)

Are we reaching closer towards understanding the Universe? The examples given above show that, perhaps, we now understand more than we did in the times of Copernicus. The development of science in the 20th and 21st centuries demonstrates that the deterministic model no longer functions. But is the model currently created a dynamic one? Are we capable of crossing "the Universe's event horizon"? Do we understand what initial instability is and is not, and is this understanding our "categorical imperative"?