DOI: 10.24425/academiaPAS.2024.151180

Łukasz Tychoniec, PhD
studies the early stages of star and planet formation using the James Webb Space Telescope and the ALMA radio telescope array.
tychoniec@strw.leidenuniv.nl

A Star Is Born

The process of star formation produces some simply mesmerizing spectacles. Studying it can also teach us about our own origins.

Łukasz Tychoniec

Leiden Observatory
Leiden University in the Netherlands

Stars evoke a sense of permanence and constancy. Sirius, Vega, the North Star, and many others were well known to the ancients, and even if their positions change slightly, they will remain in our sky for billions of years. Stars similar to the Sun live for about 10 billion years. On cosmic time scales, the process of star formation happens in the blink of an eye – it takes just a few million years for a disordered cloud of gas and dust to form a brightly shining ball of hot plasma along with its surrounding planets. We could liken this to the scale of a human lifetime: if a star lived for 100 years, its formation would take about a month. The key stage of this process, when the star acquires most of its mass, would last about two days. This brief period is what we can call the star's "youth."

Fireworks

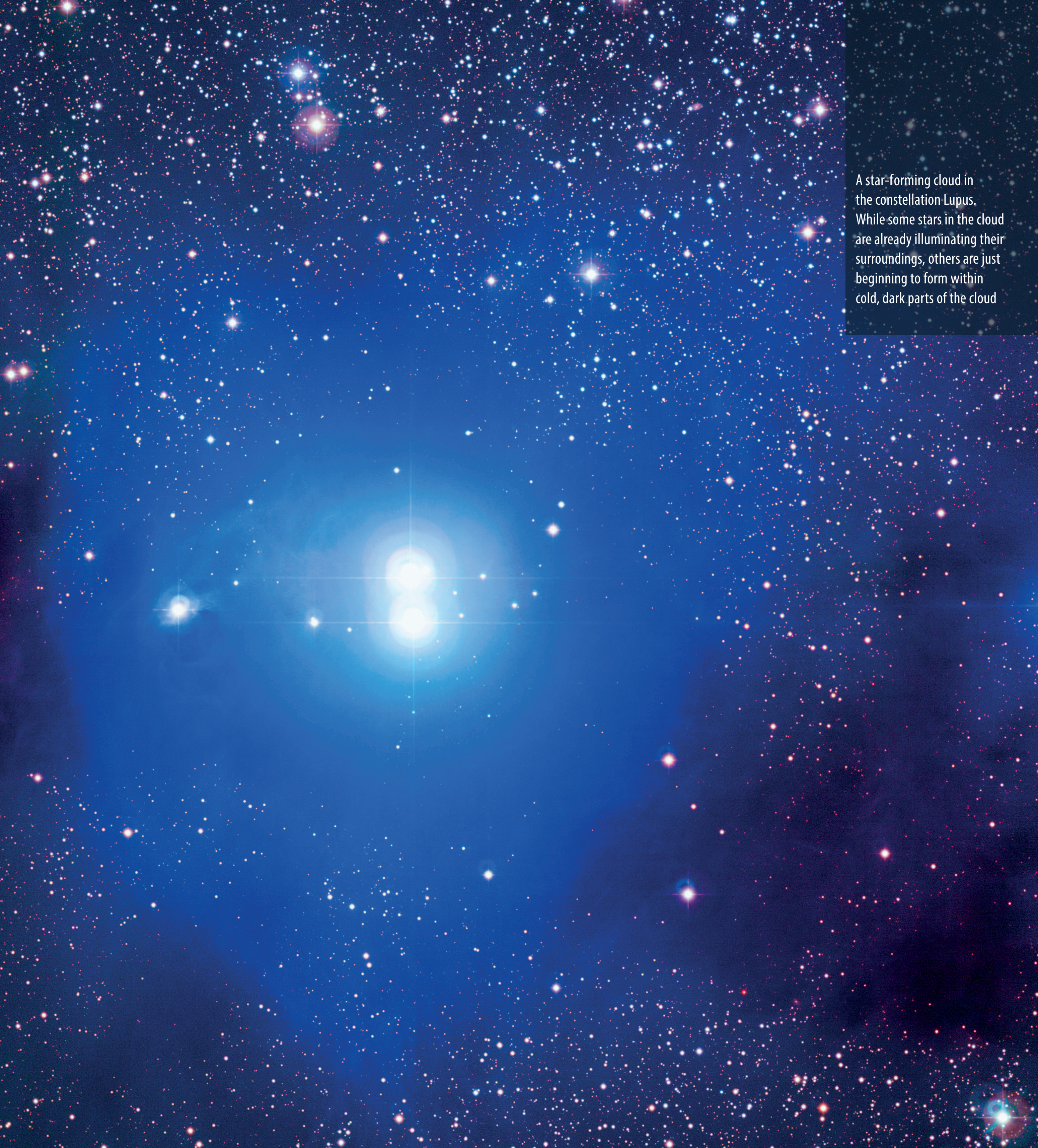
The birth of a star begins in cold darkness, within clouds so dense they obscure the light of stars behind them. These clouds of gas and dust create the perfect conditions for a new star to form. We call these *molecular clouds* because the hydrogen in them takes the form of molecules (H_2) – unlike in typical interstellar space, where it usually occurs in atomic form.

Observing such molecular clouds is not easy, as cold objects do not emit visible light. One trick astronomers use involves leveraging the light from stars behind these clouds. This light penetrates the interstellar dust, which absorbs it and thereby reveals its composition. The James Webb Space Telescope (JWST) is particularly sensitive to infrared radiation. This sensitivity has allowed us to identify the key ingredients making up the dust grains present in interstellar clouds: water, methanol, ethanol, ammonia, and carbon dioxide, helping us better understand the primordial composition of the matter that eventually forms stars and planets.

As such a cloud collapses under its own weight, at its heart a central object starts to form, still too cool to be called a star. The collapsing cloud has some initial rotation, which gradually accelerates, causing the cloud to flatten slightly. Around the embryonic protostar at its center, a disc of gas and dust forms. From this point onward, the disc will mediate in the transfer of material from the cloud to the star. The disc is also where planets begin to form.

The nascent star announces its birth by ejecting vast amounts of gas and dust out into space, throwing out about a third of the material in the process.

ESO/F. COMERON



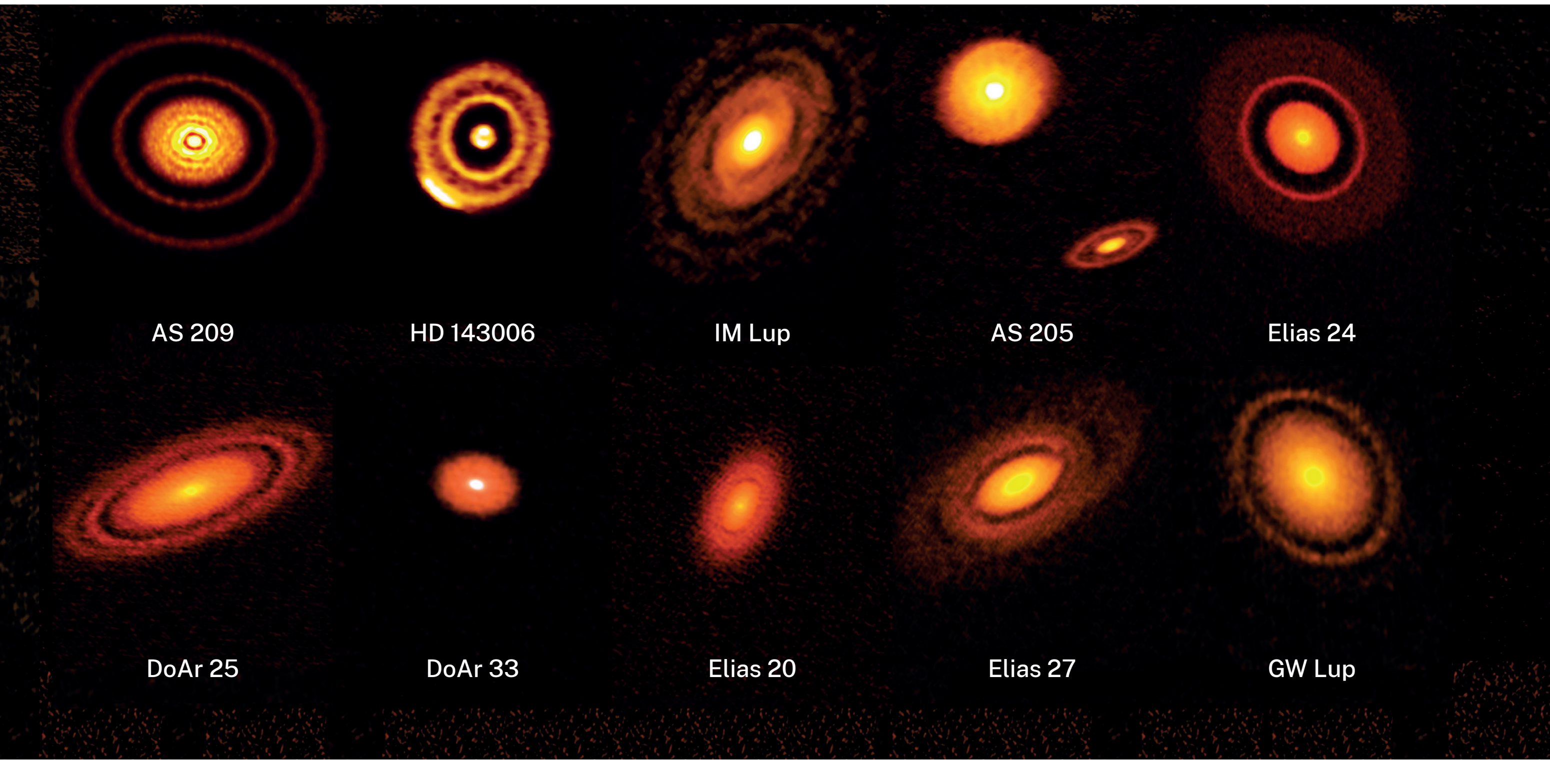
A star-forming cloud in the constellation Lupus. While some stars in the cloud are already illuminating their surroundings, others are just beginning to form within cold, dark parts of the cloud

We can observe these protostellar jets, which can be described as stunning displays of “cosmic fireworks.”

These gas streams, accelerated to hundreds of kilometers per second, create significant disturbances in their surroundings. When they collide with the cold cloud surrounding the protostar, they heat it up until it glows, thereby making the gas observable through telescopes. Over the years, protostellar jets have become a crucial element in studying protostars. If we know our distance to the protostar and the speed of the jet, we can fairly easily calculate its age. We can also study the composition of the dust ejected from the disc by the jets.

Cradles of planets

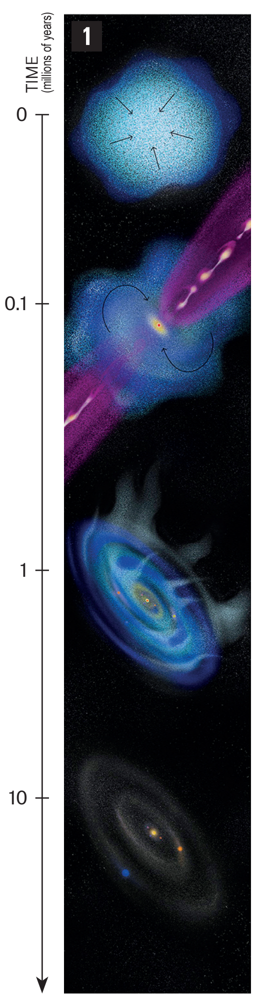
As a result of protostellar jets and stellar winds, the cloud surrounding a new star eventually disperses, revealing to us the protoplanetary disk. Such a young star still experiences turbulent times, flaring up and



ALMA (ESO/NAOJ/NRAO), S. ANDREWS ET AL.; NRAO/AUI/NSF, S. DAGNELLO

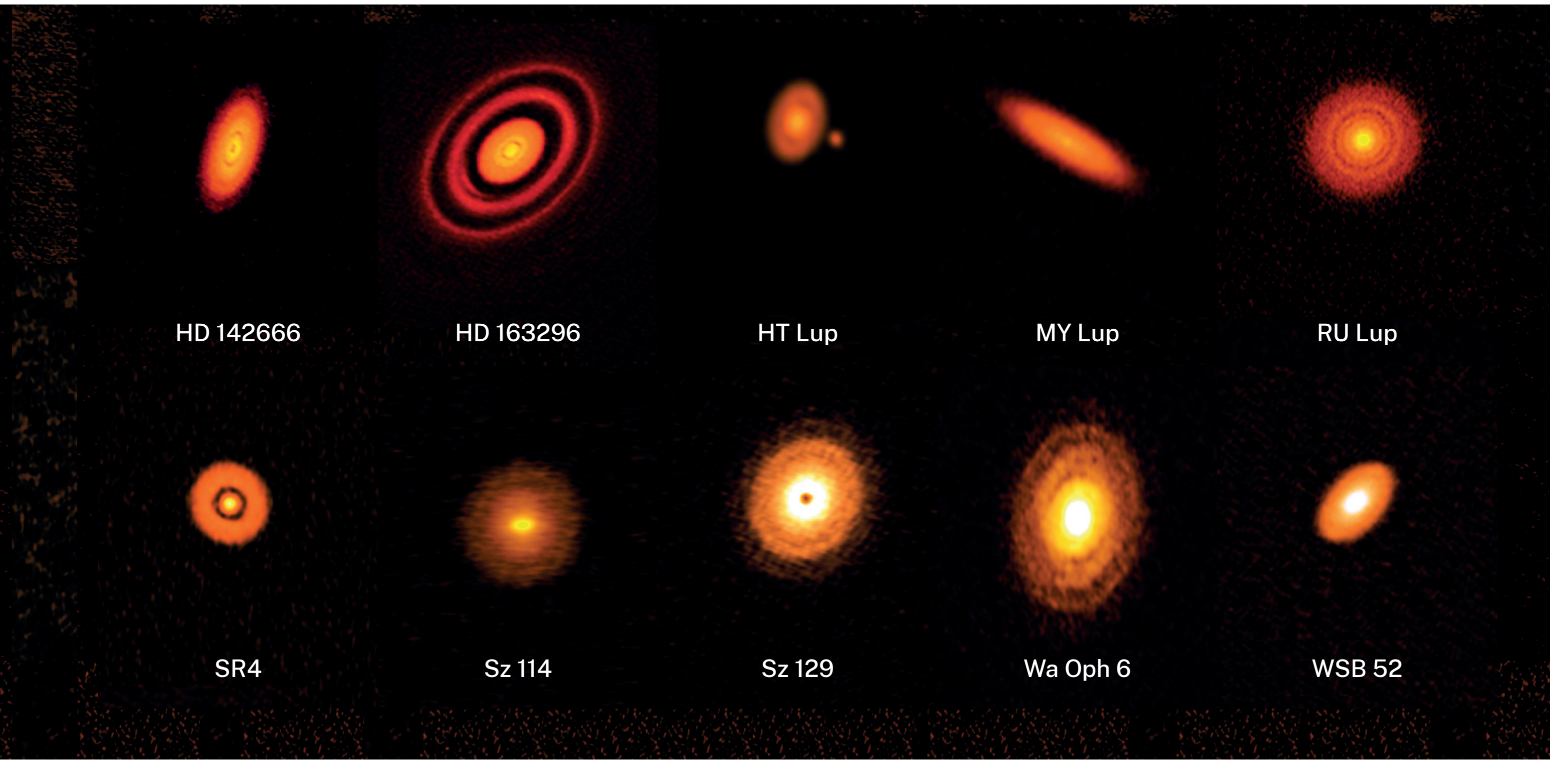
Fig. 1
A schematic representation of the star formation process: from a cool cloud of gas and dust, through an illuminated protostar with a supersonic jet and a disk with forming planets, to a mature star surrounded by planets

Fig. 2
A young protostar (around 10,000 years old) announces its birth with a spectacular supersonic ejection of gas: a protostellar jet



MARTA TYCHONIEC

ESA/WEBB, NASA, CSA, TOM RAY (DUBLIN)



ALMA (ESO/NAOJ/NRAO), S. ANDREWS ET AL.; NRAO/AUI/NSF, S. DAGNELLO

sometimes consuming the remnants of its disk. For a long time, it was believed that planet formation began only at this stage. However, with the advent of the most powerful radio interferometer, the Atacama Large Millimeter/submillimeter Array (ALMA), scientists have made a surprising observation. Many of these disks already show signs of planet-formation – they contain numerous rings and gaps, suggesting that planets are already forming.

A dense protoplanetary disc is an excellent place for dust grains to coalesce. While in outer space we rarely observe grains larger than 10 μm (0.01 mm), within such a disc, they can merge into pebbles on the centimeter scale within a few hundred thousand years.

The largest protoplanets, reaching masses of several tens of Earth masses, are massive enough to attract gas from the disc. This is how gas giants similar to our Jupiter are formed. On a cosmic scale, this process is very rapid – it takes a few million years because the material in the disk that is not used in planet formation either falls onto the star or "evaporates" due to the increasingly intense radiation from the star itself.

Just as protostellar jets announce the birth of a star, the emergence of solar wind signals the end of this process. The increasingly bright star disperses the remnants of the disk, and what remains forms a planetary system. For a star to be considered mature, it must ignite nuclear reactions in its core. Once it has gathered enough gas, the density and temperature inside will cause hydrogen atoms to fuse into helium, releasing enormous amounts of energy. This fusion is a very efficient energy source – the star will burn hydrogen steadily for the next several billion years.

Our Sun

Our galaxy is full of clouds where stars are currently forming. The clouds in the constellations of Taurus, Perseus, and the spectacular Orion Nebula are among the closest star-forming regions to us, all within a radius of 2000 light-years. Observing them can teach us about how stars form today and also about how our own Sun formed 4.5 billion years ago.

Our knowledge of the chemical composition of the Earth and the Sun tells us that the Sun originally formed in the vicinity of what was once a massive star, which exploded and enriched the surrounding area with the heavier elements that are now found in the Earth's crust.

Using the most advanced tools, including the JWST telescope and the ALMA interferometer network, we can trace the process of star and planet formation in fine detail. Both instruments also provide key information for unraveling one of science's greatest mysteries: how did life on Earth originate, and how common is it in the Universe? Studies of the chemical composition of nascent stars reveal that the "seeds of life" – simple organic molecules – turn out to be abundantly available in molecular clouds, even before star formation begins. ■

Observations using the ALMA radio telescope array have brought about a breakthrough in our understanding of planet formation – many stellar discs turn out to have structures indicating that the planet-building process has already begun

Further reading:

McClure M.K. et al., An Ice Age JWST inventory of dense molecular cloud ices, *Nature Astronomy* 2023, doi: 10.1038/s41550-022-01875-w

Ray T. et al., Outflows from the youngest stars are mostly molecular, *Nature* 2023, doi: 10.1038/s41586-023-06551-1

Stahler S.W., Palla F., *The Formation of Stars*, 2004, doi: 10.1002/9783527618675