JWST reveals the chemistry of disks around young stars where rocky planets form

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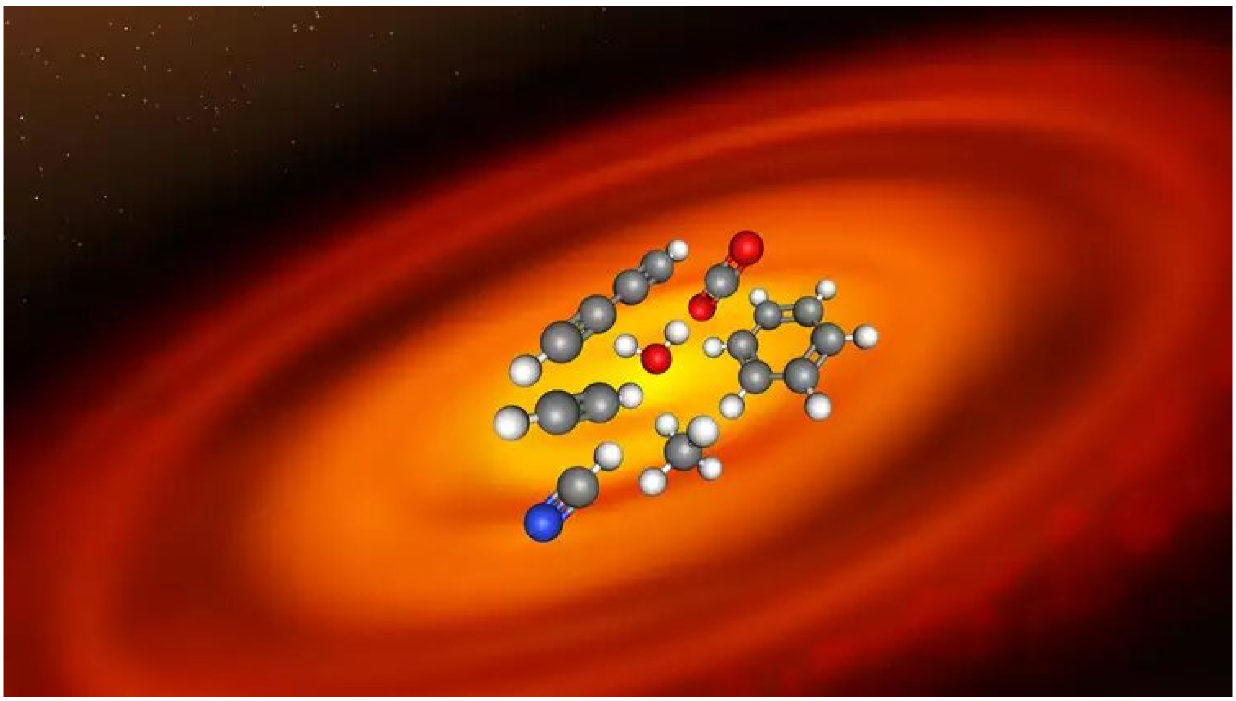


An artist's concept of a planet-forming disk around a young star. Astronomers using the MIRI spectrograph on board the JWST discovered several chemical compunds in the central regions of a first set of planet-forming disks around young stars. The molecules comprise several hydro-carbon species such as benzene and carbon dioxide, as well as water and cyanide gas. Credit: ALMA (ESO/NAOJ/NRAO) / MPIA

Researchers using the James Webb Space Telescope (JWST) have taken a first look at their data that probe the chemistry of the regions of disks around young stars where rocky planets form. Already at that stage, the data reveal the disks to be chemically diverse and rich in molecules such as water, carbon dioxide, and organic hydrocarbon compounds like benzene as well as tiny grains of carbon and silicates. The ongoing MPIA-led JWST observing program MINDS bringing together several European research institutes promises to provide a revolutionary view on the conditions that precede the birth of planets and, at the same time, determine their compositions.

New observations towards a sample of planet-forming disks around young stars obtained with the Mid-Infrared Instrument (MIRI) on board the James Webb Space Telescope (JWST) provide a first look into how this powerful tool will boost our understanding of terrestrial planet formation. Astronomers from 11 European countries have gathered in the MINDS (MIRI mid-Infrared Disk Survey) project to investigate the conditions in the inner regions of such disks where rocky planets are expected to form from the gas and dust they contain. They take the next step to decipher the conditions of planet-forming disks—a prerequisite to identifying the processes leading to solid bodies, such as planets and comets, that comprise planetary systems.

The initial results presented in two articles demonstrate the diversity of cradles of rocky planets. Disks range from environments rich in carbon-bearing compounds, including organic molecules as complex as benzene, to agglomerates containing carbon dioxide and traces of water. Like fingerprints, these chemicals produce uniquely identifiable markers in the spectra the astronomers obtained with their observations. A spectrum is a rainbow-like display of light or, as in this case, e.g., infrared radiation, splitting it into the colors of which it is composed.

"We're impressed by the quality of the data MIRI produced," says Thomas Henning, Director at the Max Planck Institute for Astronomy

(MPIA) in Heidelberg, Germany. He is the principal investigator (PI) of the JWST Guaranteed Time Observation (GTO) program MINDS. "This wealth of spectral lines does not only reveal the chemical composition of the disk material ultimately evolving into planets and their atmospheres. It also allows us to determine physical conditions like densities and temperatures across and inside those planet-forming disks, directly where the planets grow."

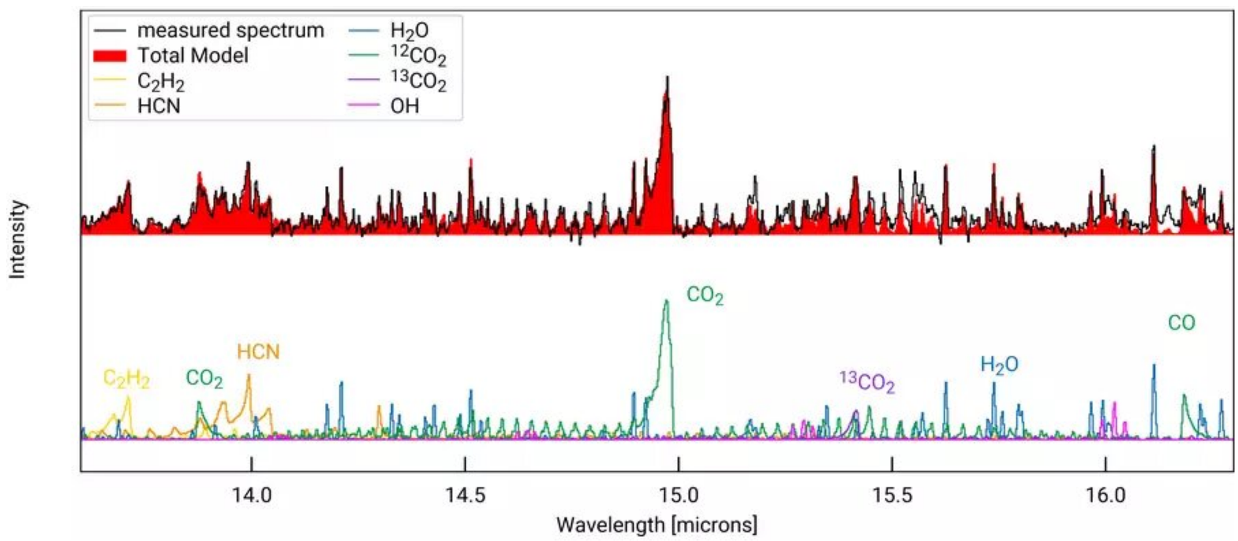
A dry protoplanetary disk with two kinds of carbon dioxide

"We can now study the chemical components in those disks much more precisely," says Sierra Grant, a post-doc at the Max Planck Institute for extraterrestrial Physics (MPE) in Garching, Germany. She is the main author of an article analyzing a disk around a young low-mass star that was published in *The Astrophysical Journal Letters*. "The warm inner disk around GW Lup appears to be rather dry. While we clearly detected molecules containing carbon and oxygen, there is much less water present than expected," Grant explains.

A gap around the central star devoid of gas would explain the lack of water. "If that hole extended until between the snowlines of water and carbon dioxide, it would explain why we find so little water vapor there," Grant says. The snowlines indicate ring-like zones at varying distances from the star where the temperatures drop to values where certain chemical species freeze out. The water snowline is closer to the star than the one for carbon dioxide.

Therefore, if a cavity extends beyond the water snowline, the gas outside this perimeter would still contain carbon dioxide but only little water. Any planet forming there would initially be fairly dry. Therefore, small icy objects like comets from the outer planetary system could be the only substantial source of water. On the other hand, if a planet interacting with the disk were responsible for such a gap, this would suggest that the planet would have accumulated water during its formation.

The team also detected for the first time a much rarer version of the carbon dioxide molecule in a protoplanetary disk containing a carbon atom that is slightly heavier than the much more frequent type. In contrast to the "normal" carbon dioxide that merely probes the warmer disk surface, the radiation of the heavier sibling can escape the disk from deeper and cooler layers. The analysis results in temperatures from around 200 Kelvin (-75 degrees Celsius) near the disk mid-plane to approximately 500 Kelvin (+225 degrees Celsius) at its surface.



This illustration shows the MIRI spectrum of the disk around the young star GW Lup in the range between 13.5 and 16.5 microns. By modelling the chemical content, the scientists reproduced the measured spectrum (top panel, black line). The total model (top panel, red area) is a combination of molecules (bottom panel) such as carbon dioxide (CO_2, green and purple), water (H_2O, blue), hydrogen cyanide (HCN, orange), hydroxyl (OH, pink), and acetylene (C_2H_2,

yellow). See also the interactive spectrum at: https://www.mpia.de/scivis/gwlup.
Credit: S. Grant et al / MPIA

Rich carbon chemistry in a disk around a very low-mass star

Life seems to require carbon, forming complex compounds. While simple carbon-bearing molecules such as carbon monoxide and carbon dioxide pervade most planet-forming disks, the rich hydrocarbon chemistry of the following disk is quite unusual.

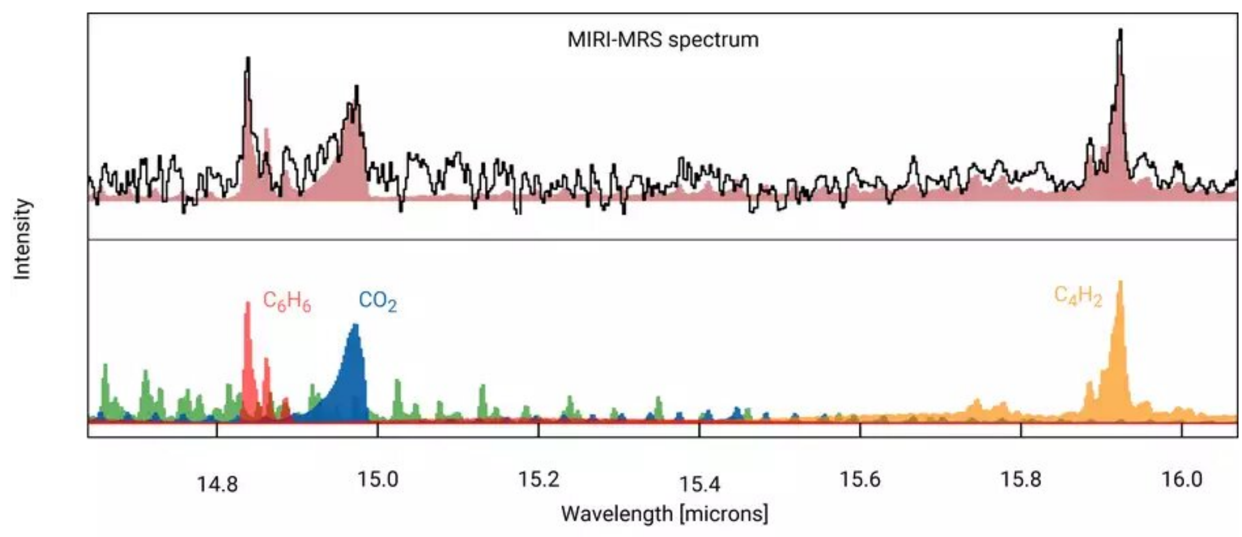
"The spectrum of the disk around the low-mass star J160532 reveals warm hydrogen gas and hydrogen-carbon compounds at temperatures around 230 degrees Celsius," says Benoît Tabone, CNRS researcher at the Institut d'Astrophysique Spatiale, Paris-Saclay University, France, and the main author of another MINDS study, which is available on the *arXiv* pre-print server. The strongest spectral signal stems from hot acetylene molecules, each consisting of two carbon and two hydrogen atoms.

Other equally warm gases of organic molecules are diacetylene and benzene, the first detections in a protoplanetary disk, and probably also methane. These detections indicate that this disk contains more carbon than oxygen. Such a mixture in chemical composition could also influence the atmospheres of planets forming there. In contrast, water seems almost absent. Instead, most of the water may be locked up in icy pebbles of the colder outer disk, not traceable by these observations.

Eruptions of young stars produce seeds for planets

Besides gas, solid material is a typical constituent of protoplanetary disks. Much of it consists of silicate grains, basically fine sand. They grow from nanoparticles to randomly structured micron-sized aggregates. When heated, they can assume crystalline structures. A work published by a team led by Ágnes Kóspál (MPIA and Konkoly Observatory, Budapest, Hungary), which is not part of the MINDS program, demonstrates how such crystals may enter the rocky pebbles that eventually build terrestrial planets. Scientists find such crystals also in comets and Earth's crust. That work is also published in *The Astrophysical Journal Letters*.

The team rediscovered crystals detected years ago in the disk around the recurrently erupting star EX Lup, just recovering from a recent outburst. It provided the necessary heat for the crystallization process. After a period of absence, these crystals now reappeared in their spectra, albeit at much lower temperatures putting them farther away from the star. This rediscovery indicates that repeated outbursts may be essential in providing some of the building blocks of planetary systems.



This illustration shows the MIRI spectrum of the disk around the young star J160532 in the range between 14.5 and 16.0 microns with the dominating acetylene emission removed. By modelling the chemical content, the scientists reproduced the measured spectrum (top panel, black line). The total model (top panel, red area) is a combination of molecules (bottom panel) such as carbon dioxide (CO_2, blue), benzene (C_6H_6, red), acetylene (C_2H_2, green), and diacetylene (C_4H_2, orange). See also the interactive spectrum at: https://www.mpia.de/scivis/j160532. Credit: B. Tabone et al / MPIA

A golden age of astronomical research

These results show that JWST's arrival ushers in a new golden age in astronomical research. Already at that early stage, the findings are groundbreaking. "We're looking forward to what other news JWST will bring," Henning declares. Altogether, the MINDS program will target the disks of 50 young low-mass stars. "We're eager to learn about the diversity we'll find."

"By refining the models used to interpret the spectra, we will also improve the results at hand. Eventually, we want to exploit JWST's and MIRI's full capabilities to examine those planetary cradles," adds Inga Kamp, a MINDS collaborator and a scientist at Kapteyn Astronomical Institute of the University of Groningen, The Netherlands.

Learning about the formation of planets around very low-mass stars, i.e., stars about five to ten times less massive than the sun, is particularly rewarding. Rocky planets are over-abundant around those stars, with many potentially habitable planets already detected. Therefore, the MINDS program promises to clarify some of the key questions about the formation of Earth-like planets and perhaps the emergence of life.

Background information

The James Webb Space Telescope (JWST) is the largest, most powerful telescope ever launched into space. It is an international partnership between NASA, ESA and CSA.

JWST's Mid-InfraRed Instrument (MIRI), built by a European consortium of research institutions, is a multi-purpose scientific instrument for infrared wavelengths between 5 and 28 microns. It combines an imaging camera with a spectrograph. With the support of industrial partners, MPIA provided the mechanisms of all wavelength-selecting elements, such as filter and grating wheels, and led MIRI's electrical design.

More information: Sierra L. Grant et al, MINDS. The Detection of 13CO2 with JWST-MIRI Indicates Abundant CO_2 in a Protoplanetary Disk, *The Astrophysical Journal Letters* (2023). DOI: 10.3847/2041-8213/acc44b

B. Tabone et al, A rich hydrocarbon chemistry and high C to O ratio in the inner disk around a very low-mass star, *arXiv* (2023). DOI: 10.48550/arxiv.2304.05954

Ágnes Kóspál et al, JWST/MIRI Spectroscopy of the Disk of the Young Eruptive Star EX Lup in Quiescence, *The Astrophysical Journal Letters* (2023). DOI: 10.3847/2041-8213/acb58a

Provided by Max Planck Society

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