James Webb Space Telescope primed to lift the haze surrounding sub-Neptunes

November 18 2021, by Margaret Carruthers

Illustration comparing the sizes of sub-Neptune exoplanets TOI-421 b and GJ 1214 b to Earth and Neptune. Both TOI-421 b and GJ 1214 b are in between Earth and Neptune in terms of radius, mass, and density. The low densities of the two exoplanets indicates that they must have thick atmospheres. The planets are arranged from left to right in order of increasing radius and mass:

- Image of Earth from the Deep Space Climate Observatory: Earth is a rocky planet with an average radius of roughly 6,370 kilometers, a mass of about 6 billion trillion metric tons, and a density 5.5 times that of water.
- Illustration of TOI-421 b: TOI-421 b is a hot sub-Neptune exoplanet with a radius 2.68 times Earth, a mass 7.2 times Earth, and a density 2.05 times water.
- Illustration of GJ 1214 b: GJ 1214 b is a warm sub-Neptune exoplanet

with a radius 2.74 times Earth, a mass 8.2 times Earth, and a density 2.2 times water.
- Image of Neptune from Voyager 2: Neptune is an ice giant with a radius 3.88 times that of Earth (giving it a volume nearly 58 times Earth), a mass 17 times Earth, and a density of only 1.6 times water.

The illustration shows the planets to scale in terms of radius, but not location in space or distance from their stars. While Earth and Neptune orbit the Sun, TOI-421 b orbits a sun-like star roughly 244 light-years away, and GJ 1214 b orbits a small red dwarf star about 48 light-years away. Credit: NASA, ESA, CSA, and D. Player (STScI)

More than half of the sun-like star systems surveyed in the Milky Way harbor a mysterious type of planet unlike any in our own solar system.

Larger than Earth, smaller than Neptune, and orbiting closer to their stars than Mercury orbits the sun, these warm-to-hot sub-Neptunes are the most common type of planet observed in the galaxy. But although researchers have been able to measure basic properties—including size, mass, and orbit—of hundreds of these planets, their fundamental nature remains unclear.

Are they dense, Earth-like balls of rock and iron, blanketed in thick layers of hydrogen and helium gas? Or less dense mixtures of rock and ice, surrounded by steamy, water-rich atmospheres? With limited data and no planets of similar size and orbit in our own solar system to use for comparison, it has been difficult to answer these questions.

"What are these planets? How do they form? Why doesn't our solar system have them? These are fundamental questions," explains Jacob Bean, an astronomer at the University of Chicago who has led numerous observations of exoplanets.

The Haze Problem

The key to figuring out what sub-Neptunes are made of and how they formed is examining their atmospheres. But getting a clear view has not been easy.

The most effective method of analyzing exoplanet atmospheres is a technique known as transmission spectroscopy. When the planet is transiting its star, some wavelengths (colors) of starlight are filtered out by gases in the planet's atmosphere. Because each type of gas has a unique "signature," or set of wavelengths that it absorbs, it's possible to figure out what an atmosphere is made of based on patterns in the transmission spectrum.

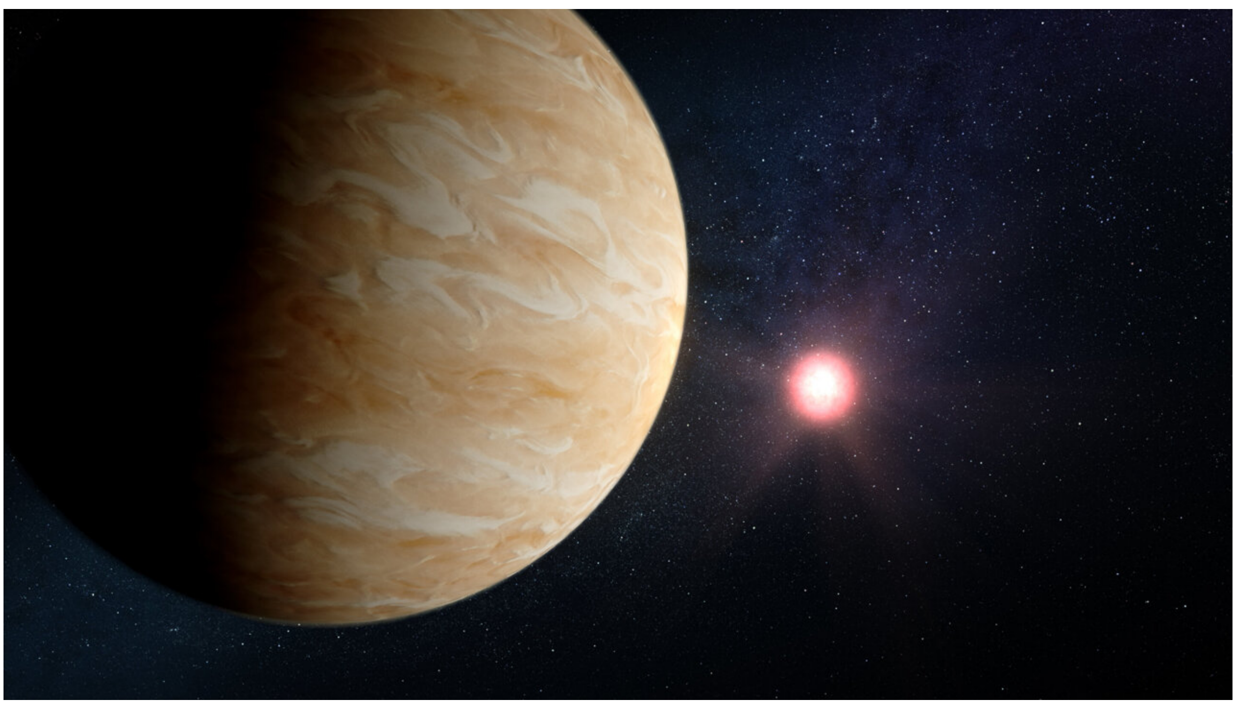

Illustration showing what exoplanet GJ 1214 b could look like based on current information. GJ 1214 b, a warm sub-Neptune-sized exoplanet roughly 48 light-years from Earth, is one of the most studied exoplanets in the galaxy. Previous spectroscopic observations indicate that the planet is shrouded in aerosols (clouds or haze), which have thus far made it impossible to determine the composition of gases that make up its thick atmosphere. Credit: NASA, ESA, CSA, and D. Player (STScI)

This technique has been successful for many exoplanets, but not for most sub-Neptunes. "There have been very few atmospheric observations of sub-Neptune planets," explains Eliza Kempton of the University of Maryland–College Park, who specializes in theoretical modeling of exoplanet atmospheres. "And most of those have been dissatisfying in that the spectra have not revealed much in the way of spectral features that would allow us to identify the gases in the atmosphere."

The issue seems to be aerosols, tiny particles and droplets that make up clouds or haze. These particles scatter starlight, eroding the prominent spectral peaks into subtle undulations and rendering the spectrum virtually useless in terms of determining gas composition.

But with Webb, researchers are confident that a much clearer view of sub-Neptunes is on the horizon. Two observation programs co-led by Bean and Kempton and scheduled for the first year of Webb operations will use Webb's uniquely powerful capabilities to probe two sub-Neptune-sized planets: GJ 1214 b, the archetype sub-Neptune; and TOI-421 b, a more recent discovery.

The Sub-Neptune Archetype: GJ 1214 b

GJ 1214 b, a warm sub-Neptune orbiting a nearby red dwarf star, has been the subject of dozens of investigations. Its short orbital period, large size relative to its star, and comparative proximity to Earth make it easy (as exoplanets go) to observe effectively, while its status as the benchmark sub-Neptune—and, according to Bean, "the most mysterious exoplanet that we know of"—make it a worthy target of investigation.

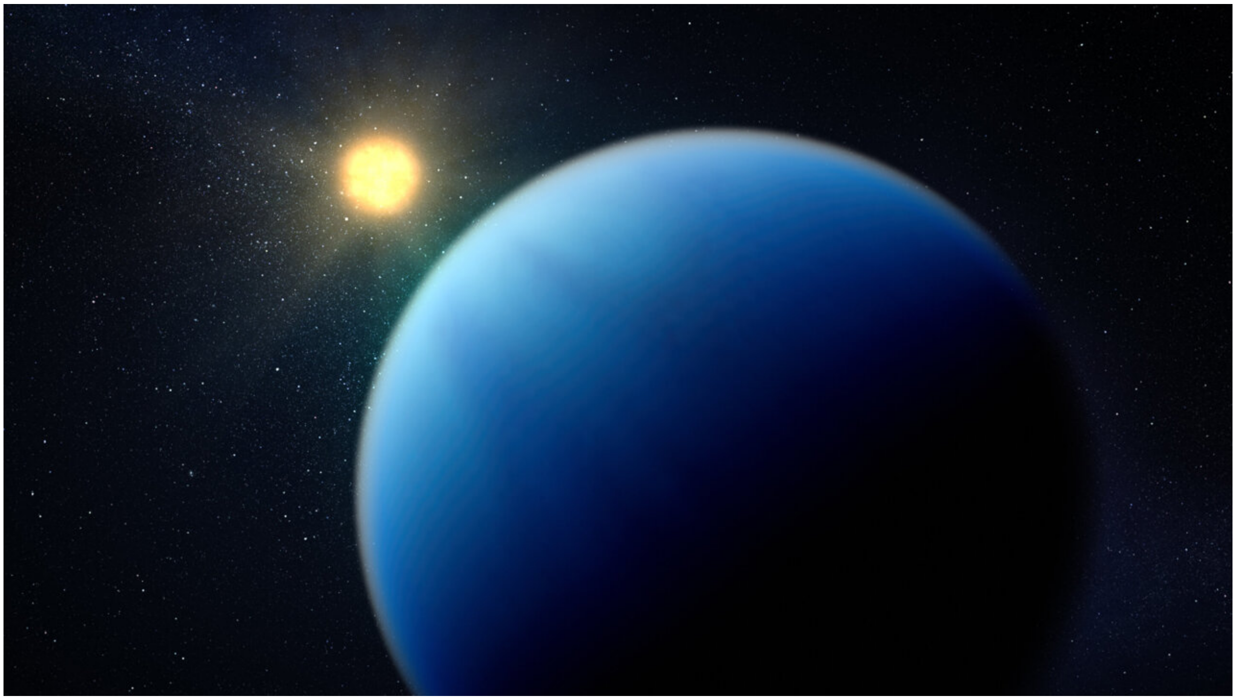

Illustration of what exoplanet TOI-421 b might look like. TOI-421 b is a hot sub-Neptune-sized exoplanet orbiting a Sun-like star roughly 244 light-years from Earth. TOI-421 b is thought to have a clear atmosphere free of haze and clouds. Credit: NASA, ESA, CSA, and D. Player (STScI)

The team will use Webb's Mid-Infrared Instrument (MIRI) to stare at the GJ 1214 system nearly continuously for nearly 50 hours as the planet completes a little more than one full orbit. They will then analyze the data in three different ways to narrow down the possible combinations of gases and aerosols that make up GJ 1214 b's atmosphere.

- Transmission Spectroscopy: If molecules like water, methane, or ammonia are abundant, they should be obvious in the transmission spectrum. Mid-infrared light should not be scattered by aerosols in the same way as visible and near-infrared light.
- Thermal Emission Spectroscopy: Mid-infrared light emitted by the planet itself will provide information about the planet's temperature and reflectivity, both of which are affected by the atmosphere. A planet surrounded by dark, sooty, light-absorbing haze, for example, will be warmer than one covered in bright, reflective clouds.
- Phase Curve Temperature Mapping: Although Webb will not be able to observe GJ 1214 b directly (the planet is too close to its star), it is sensitive enough to measure very subtle changes in the total amount of light from the system as the planet orbits the star. Researchers will use GJ 1214 b's phase curve, a graph of brightness versus phase (i.e., how much of the planet's day side is facing the telescope) to map the average temperature of the planet with longitude. This will provide additional information about the circulation and make-up of the atmosphere.

Hot Sub-Neptune TOI-421 b

It's not clear what the aerosols surrounding warm sub-Neptunes like GJ 1214 b are made of, but they could be similar to those that make up smog-like haze found on Saturn's moon Titan. To test this hypothesis, the researchers decided to target TOI-421 b, a planet that is similar in size and density to GJ 1214 b but is thought to be too hot for sooty haze to exist.

Webb will observe TOI-421 b twice as it transits its star, once using the Near-Infrared Imager and Slitless Spectrograph (NIRISS) and again with the Near-Infrared Spectrograph (NIRSpec), to produce a complete near-infrared transmission spectrum of the planet. If the hypothesis is correct and TOI-421 b's skies are clear, the spectrum can be used to measure the abundance of molecules like water, methane, and carbon dioxide. If it turns out that TOI-421 b has an aerosol problem after all, the team will use the data to better understand what those aerosols are made of.

Kempton and Bean are confident that by probing elusive sub-Neptune atmospheres in a number of different ways with Webb, scientists will finally begin to understand not just these two specific objects, but an entire class of planets.

Both the MIRI observations of GJ 1214 b and the NIRISS and NIRSpec observations of TOI-421 b will be conducted as part of Webb's Cycle 1 General Observers program. General Observers programs were competitively selected using a dual-anonymous review system, the same system used to allocate time on Hubble.

Provided by NASA's Goddard Space Flight Center