

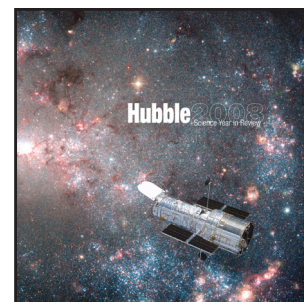
Probing the Atmospheres of Exoplanets

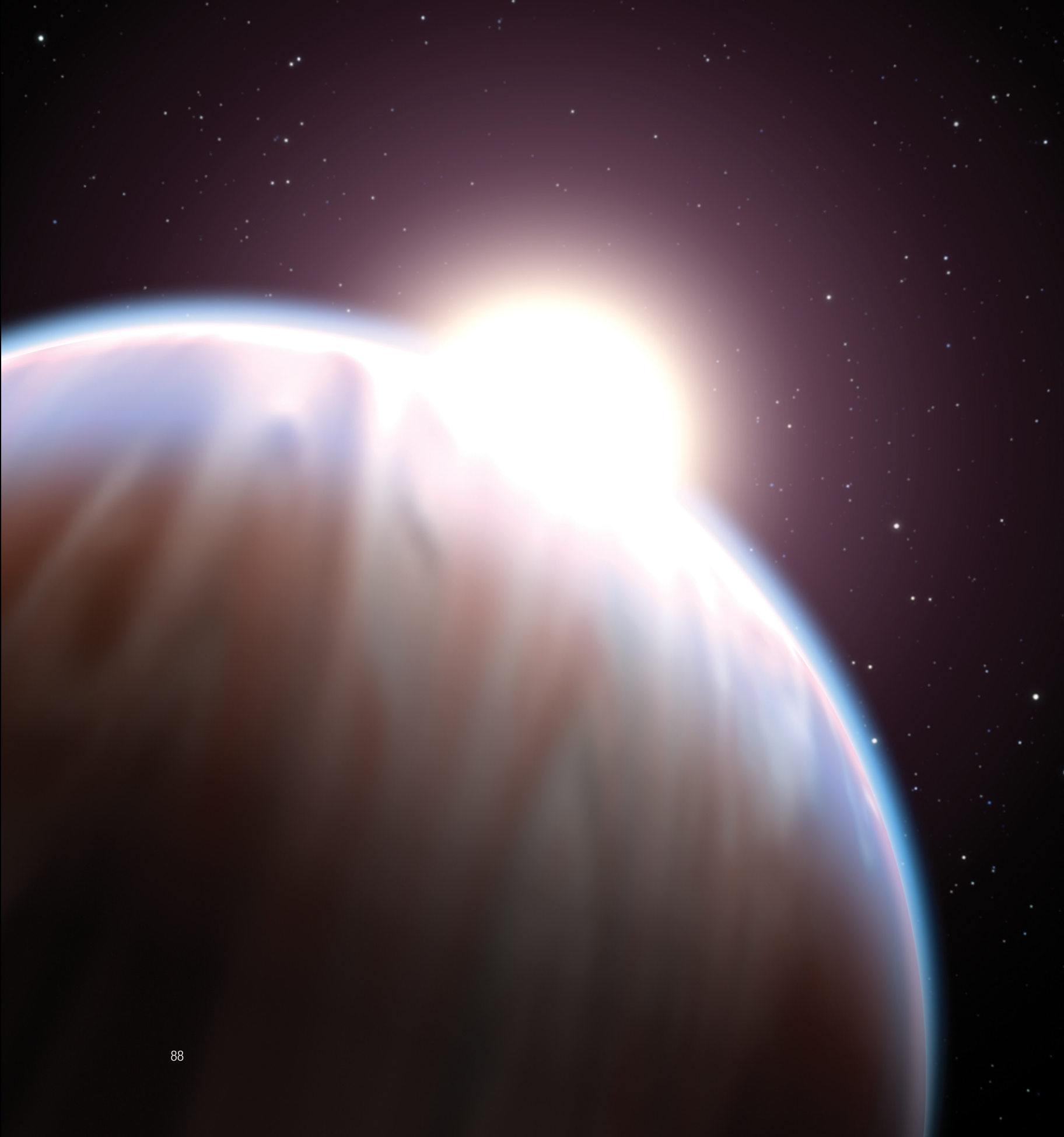
Taken from:
Hubble 2008: Science Year in Review

Produced by NASA Goddard Space Flight Center and the
Space Telescope Science Institute.

The full contents of this book include more *Hubble* science
articles, an overview of the telescope, and more. The complete
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Probing the Atmospheres of Exoplanets

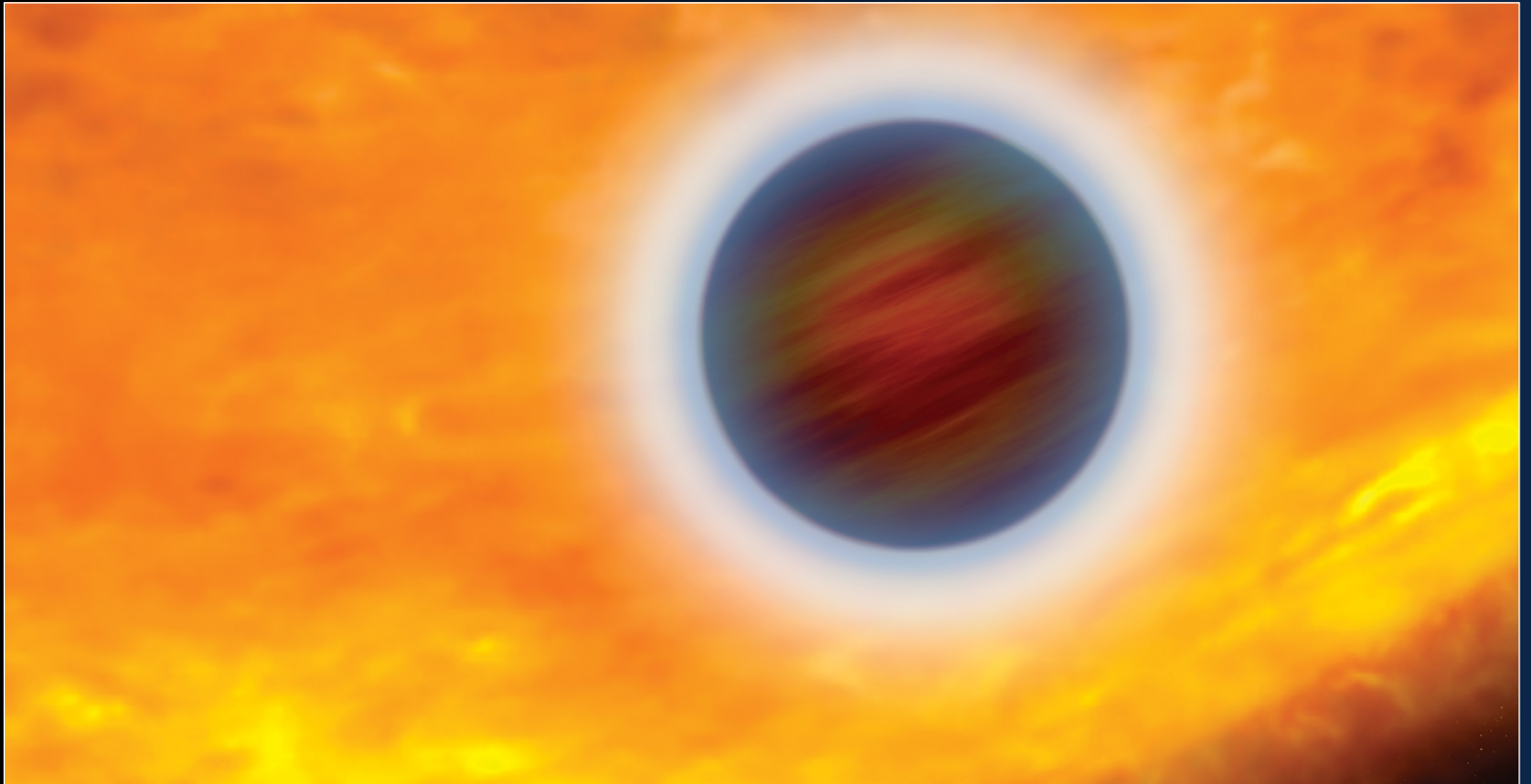
When the *Hubble Space Telescope* was launched in 1990, planets around other stars had not yet been discovered. Since 1995, however, when the first extrasolar planet, or “exoplanet,” was detected, the rate of discovery of new exoplanets and external solar systems has been truly remarkable. (Note: both “exoplanet” and “extrasolar planet” are used interchangeably in this article.) By early 2009, more than 340 planets had been found orbiting other stars—almost all of them discovered indirectly by ground-based telescopes as a result of the small, but measurable, gravitational “wobble” they impose on the stars they circle.

In the first half-decade following the initial discoveries, however, astronomers were able to derive very few characteristics about these worlds beyond their masses and basic orbital characteristics. Although it was a very important and necessary beginning to know masses and orbits, the information about exoplanets, which is most crucial to researchers exploring the possibility of life elsewhere in the universe, concerns the nature of their atmospheres. What atoms and molecules are present in an exoplanetary atmosphere and in what relative fractions? What are the temperatures and pressures? Is there evidence for cloud structure and wind patterns? Finally, when the data pertaining to all of these questions are considered, is the exoplanet’s atmosphere potentially supportive of life?

As difficult as the first discovery of exoplanets was, the detection and characterization of their atmospheres is significantly more challenging and represents a true giant step forward toward the ultimate goal: the discovery of exoplanets on which life is likely to exist. This is a journey we are just beginning, and although *Hubble* is not likely to realize the full dream, it has undeniably led the way in the exciting new field of finding and measuring exoplanetary atmospheres. At no time did the telescope’s designers in the 1970s and 1980s think that such possibilities existed. This is but one example among many of how the most exciting science to emerge from *Hubble* is often that which is unanticipated.

This artist’s concept shows exoplanet HD 189733b orbiting its parent star. *Hubble* detected the organic molecules methane, carbon dioxide, carbon monoxide, and the inorganic molecule water, in its atmosphere. The Jupiter-sized exoplanet orbits a star 63 light-years away in the constellation Vulpecula.





This artist's illustration shows extrasolar planet HD 209458b orbiting very close to its host star. The planet is about the size of Jupiter. Unlike Jupiter, the planet is so hot that its atmosphere is “puffed up.” Starlight is heating the planet's atmosphere, causing hot gas to escape into space, like steam rising from a boiler.

Exoplanet HD 209458b

The exoplanet HD 209458b is what is known as a “hot Jupiter”—a class of planet about the size of the gas giant Jupiter, but orbiting closer to its parent star than the tiny innermost planet Mercury circles the Sun. The planet's orbital period is only 3.5 days. The star, HD 209458, is a yellow, Sun-like star, visible with binoculars in the autumn constellation Pegasus, and lying approximately 150 light-years from Earth.

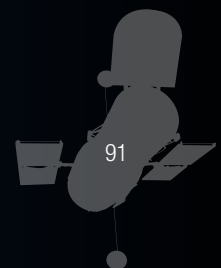
The most important aspect of the exoplanet's orbit is that it is almost “edge-on” to our line of sight, which means that once per orbit it passes in front of, or “transits,” the disk of the star. Similarly, it goes into “eclipse” once per orbit behind the star. This edge-on orbital geometry—which is shared by some other exoplanetary systems—offers profound advantages to the study of exoplanetary atmospheres. In 2001, *Hubble* was the first telescope ever to detect and begin the characterization of these atmospheres.

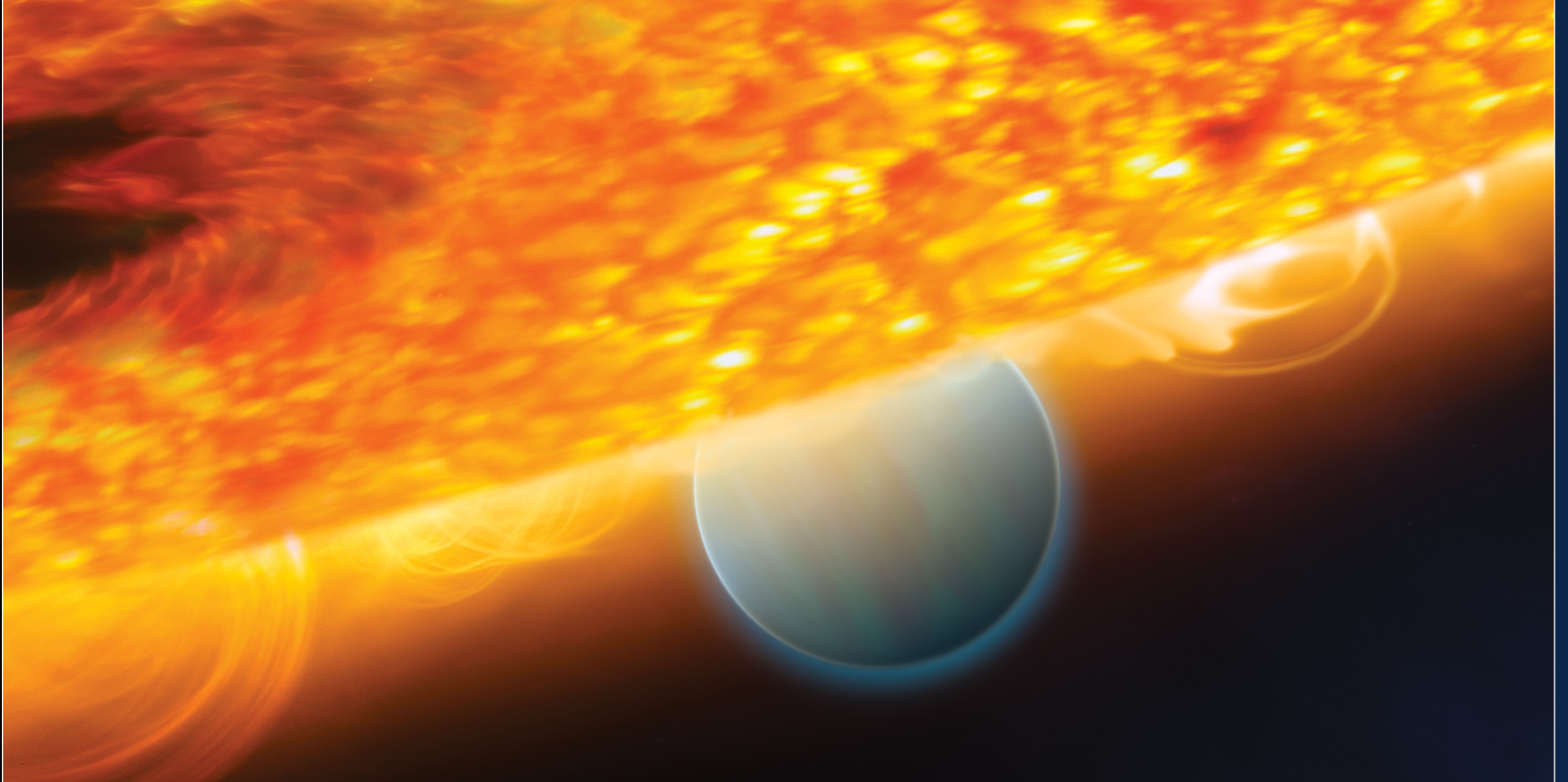
HD 209458b's atmospheric composition was probed when the planet transited the star. As the light from the parent star passed briefly through the atmosphere along the edge of the planet, the gases in the atmosphere imprinted their unique absorption signatures on the starlight.

Using this technique, Lead Investigator David Charbonneau of the Harvard-Smithsonian Center for Astrophysics used *Hubble's* Space Telescope Imaging Spectrograph (STIS) to detect the presence of sodium in the planet's atmosphere. Because the detected sodium was three times weaker than had been predicted, the researchers were able to make some tentative deductions about the existence of clouds, which act to mask—and thereby lower—the measured level of sodium. Only the precision afforded by space-based spectroscopy allowed this extraordinarily difficult measurement to be made. As of late 2008, similar attempts to detect sodium in HD 209458b with giant, ground-based telescopes far larger than *Hubble* have been unsuccessful.

In 2003, an international team of astronomers, led by Alfred Vidal-Madjar of the Institut d'Astrophysique de Paris, Centre National de la Recherche Scientifique (CNRS), France, again studying HD 209458b with *Hubble*, discovered—in the first discovery of its kind—the atmosphere of an exoplanet evaporating off into space. The planet's outer atmosphere is evidently so heated by its parent star that it begins to escape the planet's gravity. The *Hubble* observations revealed a hot and puffed-up evaporating hydrogen atmosphere surrounding and following the planet—much like the tail of a comet.

Additional observations conducted in 2007 by astronomers Gilda Ballester, David K. Sing, and Floyd Herbert, provided additional details of this gaseous envelope. Their research revealed the temperature of the layer in HD 209458b's upper atmosphere, where the gas becomes so heated it escapes. At the top of this layer, the temperature skyrockets from about 1,340 degrees Fahrenheit to as much as 26,540 degrees Fahrenheit—hotter than the surface of the Sun. Given the high evaporation rate observed, it is theorized that much of the planet may eventually disappear, leaving behind only a dense core.





This is an artist's impression of the Jupiter-sized planet HD 189733b being eclipsed by its parent star. (Figure credit: M. Kornmesser/ESA and STScI)

Exoplanet HD 189733b

Exoplanet HD 189733b was discovered orbiting the star HD 189733A in 2005, when astronomers observed the tiny drop in light from the star/planet system when the planet transited across the face of the star. Over the past few years, many additional observations have been taken of this system. Only 63 light-years away, it is the most accessible of all of the known transiting hot Jupiters. The combination of a large planet and relatively small parent star—only 76 percent of the diameter of our Sun—makes this planet comparatively easy to detect.

HD 189733b, which is slightly more massive than Jupiter, is so close to its parent star it takes just over two days to complete an orbit. At a scorching 1,700 degrees Fahrenheit, its atmosphere is about the same temperature as the melting point of silver. In 2007, a team led by Frédéric Pont from the Geneva University Observatory in Switzerland used *Hubble's* Advanced Camera for Surveys (ACS) to observe the planet. Using a special grism (a cross between a prism and a diffraction grating) within ACS, the astronomers made extremely accurate measurements of the spectrum of HD 189733b.

They had expected to see the fingerprints of sodium, potassium, and water in the spectrum—and instead detected none. This finding, combined with the distinct shape of the planet's spectrum, pointed to the presence of high level hazes in its atmosphere, which would block the anticipated spectral lines. Estimated to be at an altitude of roughly 620 miles, hazes on HD 189733b are believed to consist of tiny particles 1,000 times smaller than the diameter of a pinhead. They may be condensates of iron, silicates, and aluminum oxide dust (the compound on Earth that makes up the mineral sapphire).

Adding to the overall knowledge of HD 189733b by the group was the finding that the transiting exoplanet's light curve did not reveal the signature of any Earth-sized moons nor any discernable Saturn-like ring system. Thus, bit by bit, the presence or absence of spectral features has begun to permit real analysis of the conditions present within planetary systems around other stars.

The Latest Big News

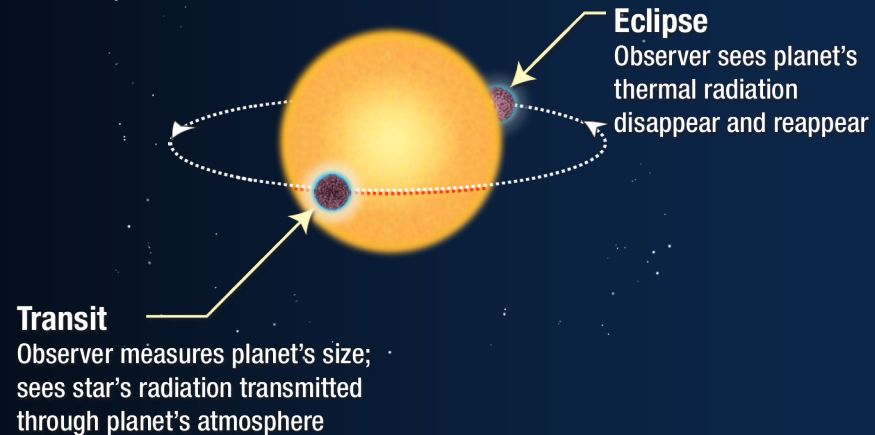
In 2008, *Hubble* enabled two other significant advances in the technique of analyzing the atmospheres of transiting/eclipsing exoplanets with the first-ever detection of an organic (carbon-bearing) molecule. Mark Swain of NASA's Jet Propulsion Laboratory in Pasadena, California led the team that made this discovery in the atmosphere of HD 189733b using extensive observations from *Hubble's* Near Infrared Camera and Multi-Object Spectrometer (NICMOS) when HD 189733b was transiting the stellar disk. The team also confirmed the existence of water molecules in the planet's atmosphere, a discovery made originally by NASA's *Spitzer Space Telescope* in 2007.

Detection of organic molecules is a crucial step toward finding evidence for life outside our solar system. The molecule detected was methane, whose chemical symbol is CH₄ and which, under the right conditions, may be produced by living organisms. Some of the very first forms of life on Earth may have been methanogens, a form of bacteria that produces methane as a metabolic byproduct. HD 189733b is too close to its star and too hot to support life as we know it. The discovery demonstrates, however, that astronomers can detect organic molecules and water in the atmospheres of distant transiting planets.



Transiting (and Eclipsed) Exoplanets

Different types of information can be gained from watching a planet pass in front of and behind its parent star as viewed from Earth.



Transits, however, are only half of the story. When HD 189733b goes into “eclipse”—that is, behind its star—astronomers are given another chance to characterize its exoplanetary atmosphere. This method looks for “what disappeared” from the combined star–planet spectrum taken before the eclipse. Spectral signatures that disappear in this way are attributed to the exoplanet itself. The reason is that the subtraction of the pure star spectrum from the combined star/planet spectrum yields the spectrum of just the exoplanet. Using NICMOS and the eclipse method, Swain and his colleagues added to the inventory of water and methane for HD 189733b by confirming carbon monoxide (CO, suggested earlier to be present by Charbonneau and colleagues) and detecting carbon dioxide (CO₂) outright. Altogether, that makes for a chemical inventory detected, to date, of water and three organic molecules in one exoplanetary atmosphere. Clearly, the detailed spectroscopic measurement of exoplanets in edge-on orbits is capable of returning extremely important information—a reality that was simply unimaginable in the 1990s.

The discovery of methane on HD 189733b is, however, not without mystery. In our solar system, methane is not seen in the hot atmosphere of Venus, but only in those planetary atmospheres much colder than Earth's. Most astronomers expected a hot planet such as this one to produce carbon monoxide, not methane. Scientists are still puzzling over its source. One explanation may be that the atmosphere in HD 189733b's night sky is cold enough to produce methane, which is then transported by fast winds to the day/night edge—the region probed in this study. Or perhaps the methane results from a chemical reaction triggered by the light from the parent star. Or even more simply, maybe it is outgassed from inside.

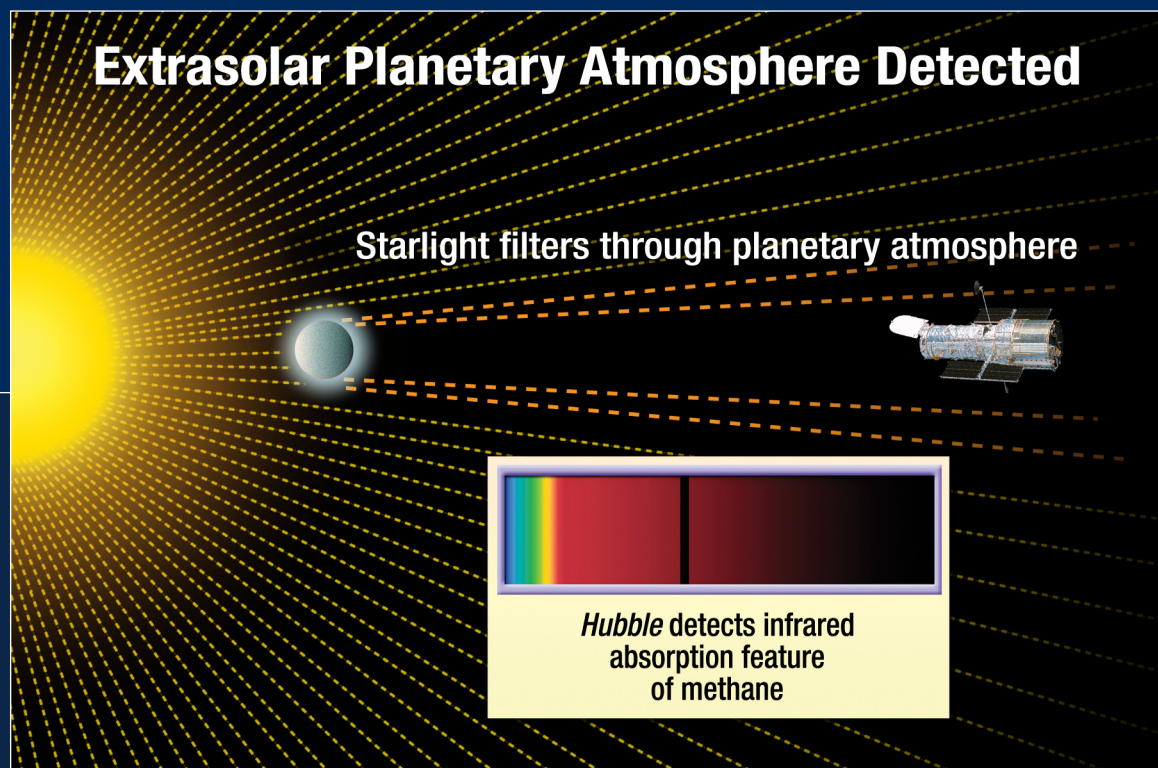
Transiting (and Eclipsed) Exoplanets

Astronomers cannot physically sample celestial objects in a laboratory the way chemists or biologists can sample the subjects of their study. Most of what we know about celestial objects comes from the light they emit, reflect, or absorb. One of the most important tools used by astronomers is spectroscopy, in which the light is broken into its component wavelengths.

When an exoplanet passes in front of its star as detected from Earth, the planet's atmosphere absorbs more of the starlight at wavelengths where the atmosphere is opaque and less at wavelengths where the atmosphere is transparent. Mark Swain and his team used *Hubble's* near-infrared NICMOS camera to construct an infrared spectrum of exoplanet HD 189733b, as seen in transmitted starlight. The planet's atmosphere soaked up infrared light in a pattern expected of methane and water molecules. It produced a spectrum that shows the distinctive absorption features of methane and water vapor in the planet's atmosphere.

Another type of spectrum, called an emission spectrum, was taken as HD 189733b passed behind its companion star. The occultation of this planet allowed the opportunity to subtract the light of the star alone—when the planet is blocked—from that of the star and planet together prior to eclipse. This allowed the isolation of the emission of the planet alone, making possible a chemical analysis of its “day-side” atmosphere. In this analysis, carbon monoxide and carbon dioxide were detected.

As starlight passes through the exoplanet's atmosphere, methane absorbs some of the light and leaves its distinctive “fingerprint.”



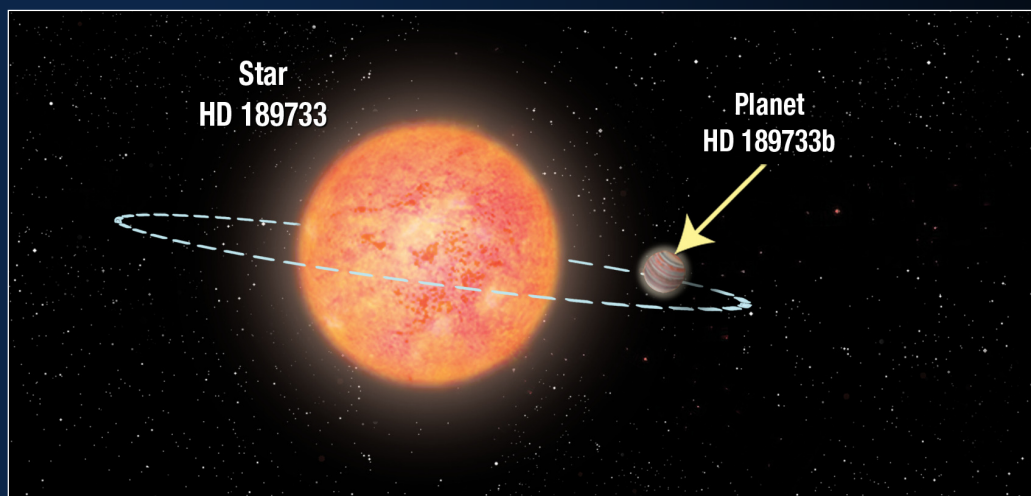
Looking Toward the Future

Hubble's observations of transiting planets are proof in concept that large, infrared-optical space telescopes can use transits and eclipses to effectively yield information about exoplanet atmospheres. With the original STIS observation of HD 209458b and the NICMOS and ACS observations of HD 189733b, three separate *Hubble* instruments have now shown their ability to contribute data in this challenging arena. Assuming the successful astronaut servicing of *Hubble* in 2009, there should be additional contributions by the observatory's two new instruments, the Cosmic Origins Spectrograph (COS) and Wide Field Camera 3 (WFC3), which also has a near-infrared grism. With these instruments operating, the number of molecules discovered is expected to grow rapidly.

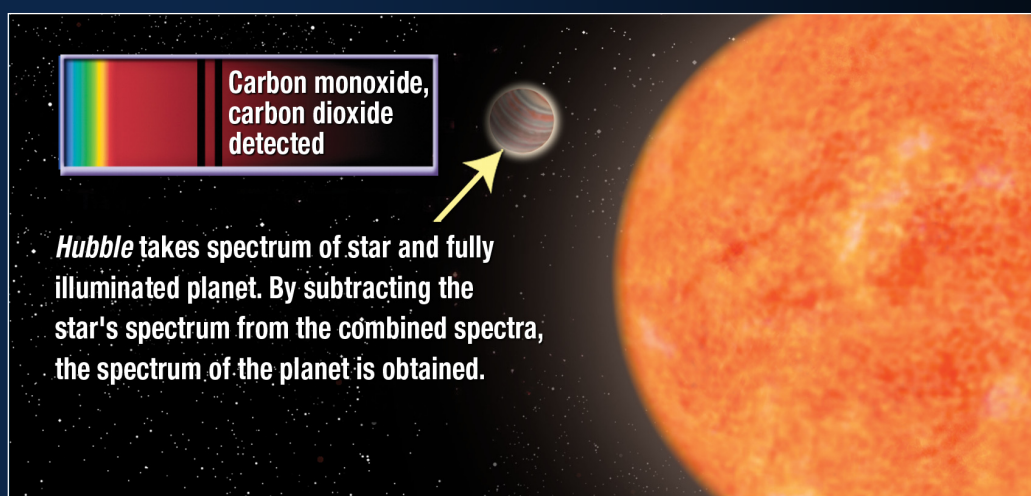
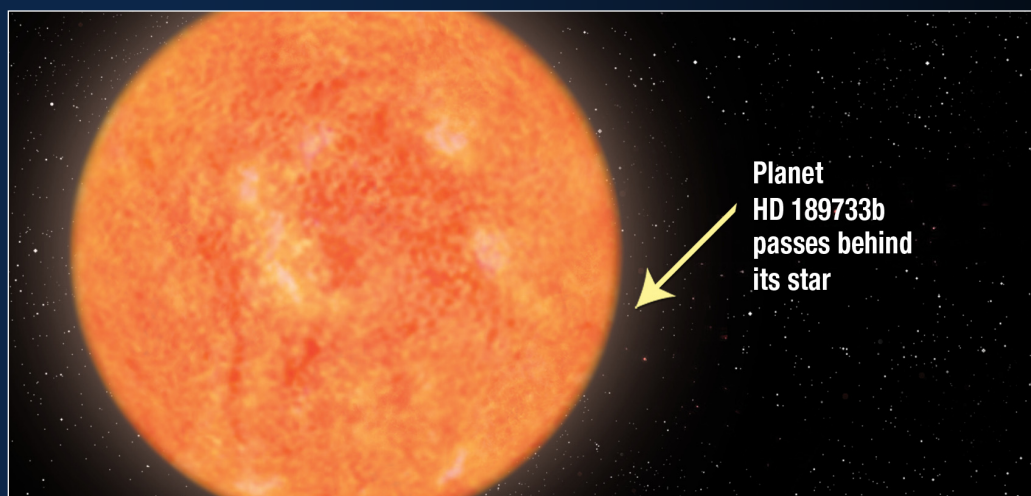
Eventually, with the larger, more sensitive *James Webb Space Telescope*, astronomers may be able to perform molecular spectroscopy at infrared wavelengths of the exoplanets that lie in a star's habitable zone. This is also a major objective for future, very large aperture ultraviolet-optical telescopes in space.

Such next-generation space telescopes will enable the possibility of actually identifying biomarkers—decisive spectral signatures that would establish that biological activity is present. These biomarkers include oxygen, ozone, methane, nitrous oxide, and chlorine. To find them, scientists would look for molecules in the exoplanet's atmosphere that are present in amounts not explainable through thermochemistry or photochemistry, but require some other mechanism for sustaining unusual abundances.

Hubble's observations of far-flung planetary systems have given us important first data in the quest to answer two grand questions: How unique is Earth, and how common is life in the universe? Using *Hubble*, *Spitzer*, *Webb*, and other planned telescopes, scientists should soon have all the necessary tools to provide us more definitive answers.



Hubble detected carbon monoxide and carbon dioxide in the atmosphere of exoplanet HD 189733b by taking the combined spectra of the star and planet, then subtracting the star's spectrum from the combined spectra.

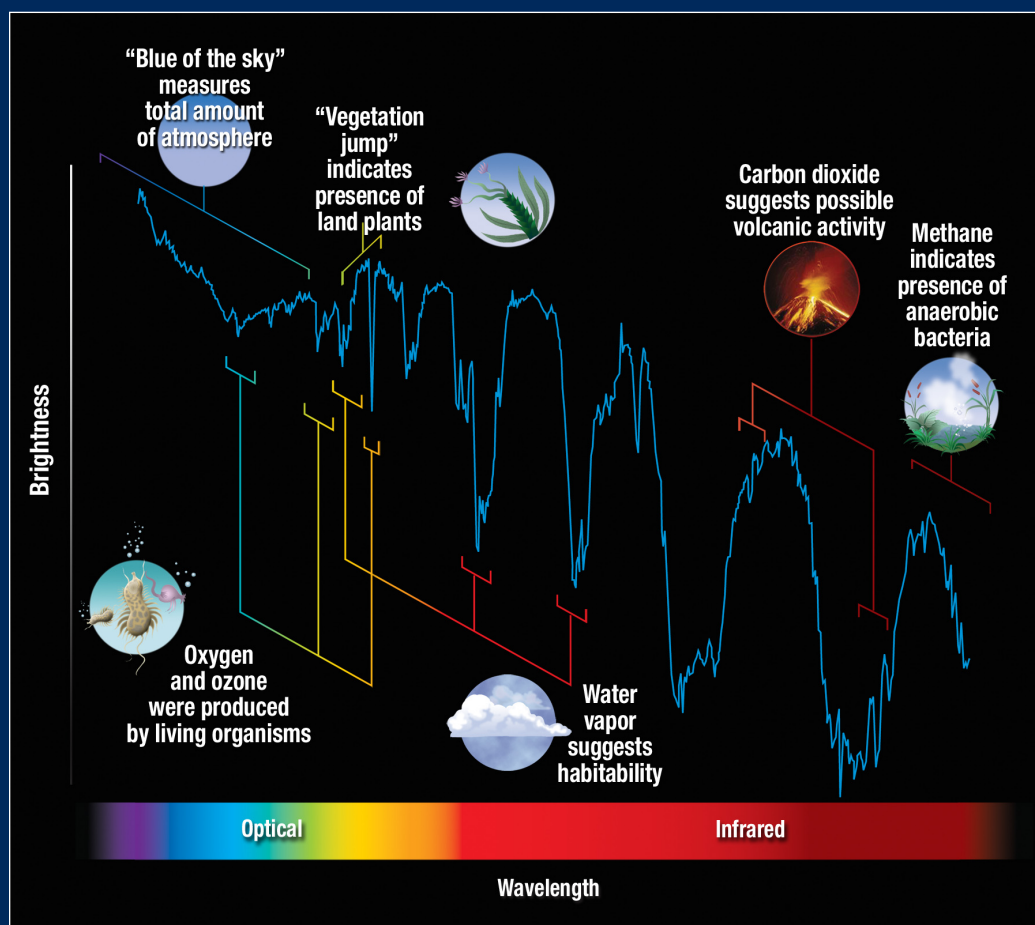


Recognizing Life

In their search for life on other planets, scientists have only one blueprint: the mix of elements such as methane, oxygen, and ozone that make up the atmosphere of Earth, a planet that orbits a comfortable distance from its star, the Sun. There could be, however, other recipes for life. Scientists may not even recognize life if they find it.

Even on Earth, salty lakes, polar ice caps, volcanic vents, and other places deemed inhospitable to life were found just a few decades ago to have colonies of hardy microbes. One way to study distant worlds for life is to make models of the environments of those possible worlds in the lab. Researchers at the Virtual Planetary Laboratory at the California Institute of Technology's Spitzer Science Center suggest that not all life will metabolize food and energy exactly like life on Earth. So, they are developing models of planets that generate alternative environments that might bear the signature of life.

One computer model they produced puts Earth around different types of stars. They placed our planet, for example, around a red dwarf—a common type of star that is not as hot as the Sun. The model predicted a decrease in the amount of ozone, but an increase in methane—both biosignature gases. The researchers thus discovered that many of the biosignature gases in the atmospheres of planets around different stars survive longer in their atmospheres and are much easier to see.



Earth's spectroscopic signatures indicate the possible conditions conducive to life.

The environments of complex planets are also expected to change over time. Earth is one example. Earth's atmosphere has dramatically changed over the last 4.6 billion years, driven largely by the actions of life.

About 2.3 billion years ago, there was a rapid rise of oxygen in Earth's atmosphere resulting from colonies of blue-green algae that produced oxygen as a waste byproduct. This eventually allowed multi-cellular life to develop by providing a new chemical source of energy, and by building the ozone layer to block our ultra-violet light that is destructive to organic compounds.

Further Reading

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Mark Swain leads an effort to identify molecules in exoplanet atmospheres using infrared spectroscopy. Results from this effort include the first detection of methane and carbon dioxide in an exoplanet atmosphere. Born in Boulder, Colorado, Swain received a B.A. in physics from the University of Virginia in 1989, and a Ph.D. in physics and astronomy from the University of Rochester in 1996. He is currently a research scientist at the Jet Propulsion Laboratory. His main scientific focus is using molecular spectroscopy to probe the conditions, composition, and chemistry of exoplanet atmospheres.

