The Color of Plants on Other

Green aliens are so passé.

On other worlds, plants could be red, blue, even black

BY NANCY Y. KIANG

KEY CONCEPTS

- What color will alien plants be? The question matters scientifically because the surface color of a planet can reveal whether anything lives there—specifically, whether organisms collect energy from the parent star by the process of photosynthesis.
- Photosynthesis is adapted to the spectrum of light that reaches organisms. This spectrum is the result of the parent star's radiation spectrum, combined with the filtering effects of the planet's atmosphere and, for aquatic creatures, of liquid water.
- Light of any color from deep violet through the near-infrared could power photosynthesis. Around stars hotter and bluer than our sun, plants would tend to absorb blue light and could look green to yellow to red. Around cooler stars such as red dwarfs, planets receive less visible light, so plants might try to absorb as much of it as possible, making them look black.

—The Editors

The prospect of finding extraterrestrial life is no longer the domain of science fiction or UFO hunters. Rather than waiting for aliens to come to us, we are looking for them. We may not find technologically advanced civilizations, but we can look for the physical and chemical signs of fundamental life processes: "biosignatures." Beyond the solar system, astronomers have discovered more than 200 worlds orbiting other stars, so-called extrasolar planets. Although we have not been able to tell whether these planets harbor life, it is only a matter of time now. Last July astronomers confirmed the presence of water vapor on an extrasolar planet by observing the passage of starlight through the planet's atmosphere. The world's space agencies are now developing telescopes that will search for signs of life on Earth-size planets by observing the planets' light spectra.

Photosynthesis, in particular, could produce very conspicuous biosignatures. How plausible is it for photosynthesis to arise on another planet? Very. On Earth, the process is so successful that it is the foundation for nearly all life. Although some organisms live off the heat and methane of oceanic hydrothermal vents, the rich ecosystems on the planet's surface all depend on sunlight.

Photosynthetic biosignatures could be of two kinds: biologically generated atmospheric gases such as oxygen and its product, ozone; and surface colors that indicate the presence of specialized pigments such as green chlo-

RED EARTH, GREEN EARTH, BLUE EARTH: Type M stars (red dwarfs) are feeble, so plants on an orbiting Earth-like world might need to be black to absorb all the available light (*first panel*). Young M stars fry planetary surfaces with ultraviolet flares, so any organisms must be aquatic (*second*). Our sun is type G (*third*). Around F stars, plants might get too much light and need to reflect much of it (*fourth*).

KENN BROWN AND CHRIS WREN *Mondolithic Studios*

Worlds

[TIMELINE OF PHOTOSYNTHESIS ON EARTH]

Photosynthesis evolved early in Earth's history. The rapidity of its emergence suggests it was no fluke and could arise on other worlds, too. As organisms released gases that changed the very lighting conditions on which they depended, they had to evolve new colors.

▼ Formation of Earth — 4.6 billion years ago (Ga) — 4 Ga — 3.4 Ga ▲ — 3 Ga — 2.7 Ga ▲ — First rock evidence of atmospheric oxygen (2.4–2.3 Ga) ▼ — 2 Ga

First photosynthetic bacteria They absorbed near-infrared rather than visible light and produced sulfur or sulfate compounds rather than oxygen. Their pigments (possibly bacteriochlorophylls) were predecessors to chlorophyll.

Cyanobacteria These ubiquitous bacteria were the first oxygen producers. They absorb visible light using a mix of pigments: phycobilins, carotenoids and several forms of chlorophyll.

Red and brown algae These organisms have more complex cellular structures than bacteria do. Like cyanobacteria, they contain phycobilin pigments as well as various forms of chlorophyll.

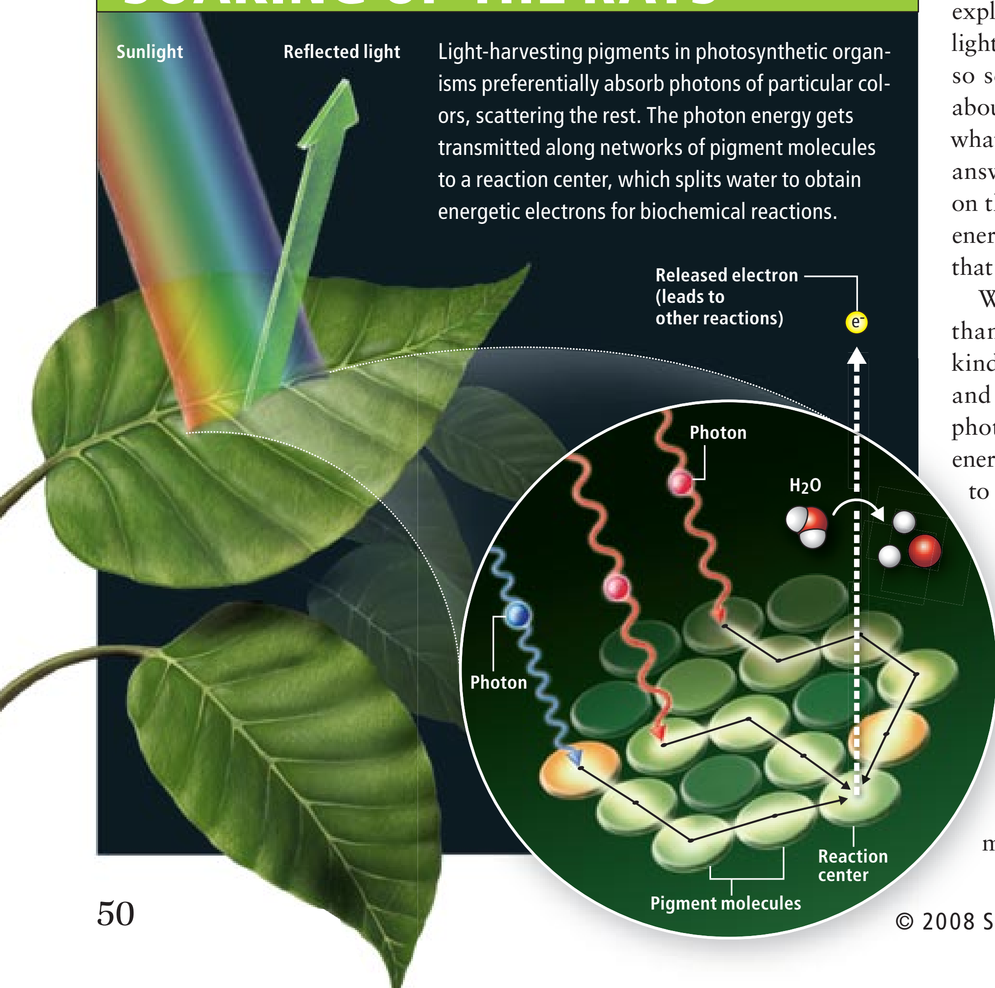
Green algae Green algae do better than red and brown algae in the strong light of shallow water. They make do without phycobilins.

rophyll. The idea of looking for such pigments has a long history. A century ago astronomers sought to attribute the seasonal darkening of Mars to the growth of vegetation. They studied the spectrum of light reflected off the surface for signs of green plants. One difficulty with this strategy was evident to writer H. G. Wells, who imagined a different scenario in *The War of the Worlds:* "The vegetable kingdom in Mars, instead of having green for a dominant colour, is of a vivid blood-red tint." Although we now know that Mars has no surface vegetation (the darkening is caused by dust storms), Wells was prescient in speculating that photosynthetic organisms on another planet might not be green.

Even Earth has a diversity of photosynthetic organisms besides green plants. Some land plants have red leaves, and underwater algae and photosynthetic bacteria come in a rainbow of colors. Purple bacteria soak up solar infrared radiation as well as visible light. So what will dominate on another planet? And how will we know when we see it? The answers depend on the details of how alien photosynthesis adapts to light from a parent star of a different type than our sun, filtered through an atmosphere that may not have the same composition as Earth's.

[PHOTOSYNTHESIS 101]

SOAKING UP THE RAYS



Light-harvesting pigments in photosynthetic organisms preferentially absorb photons of particular colors, scattering the rest. The photon energy gets transmitted along networks of pigment molecules to a reaction center, which splits water to obtain energetic electrons for biochemical reactions.

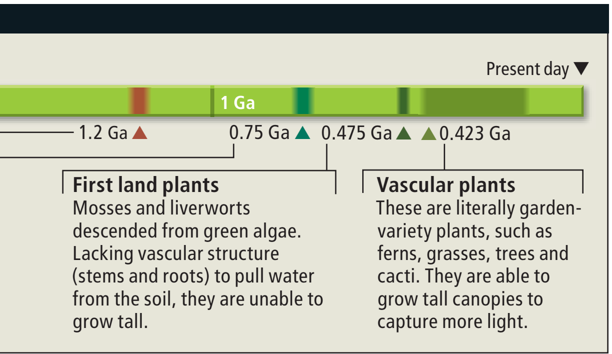
LISA APPELBACHER

Harvesting Light

In trying to figure out how photosynthesis might operate on other planets, the first step is to explain it on Earth. The energy spectrum of sunlight at Earth's surface peaks in the blue-green, so scientists have long scratched their heads about why plants reflect green, thereby wasting what appears to be the best available light. The answer is that photosynthesis does not depend on the total amount of light energy but on the energy per photon and the number of photons that make up the light.

Whereas blue photons carry more energy than red ones, the sun emits more of the red kind. Plants use blue photons for their quality and red photons for their quantity. The green photons that lie in between have neither the energy nor the numbers, so plants have adapted to absorb fewer of them.

The basic photosynthetic process, which fixes one carbon atom (obtained from carbon dioxide, CO_2) into a simple sugar molecule, requires a minimum of eight photons. It takes one photon to split an oxygen-hydrogen bond in water (H_2O) and thereby to obtain an electron for biochemical reactions. A total of four such bonds must be broken to create an oxygen molecule (O_2). Each of those photons is matched by at least one additional photon for



a second type of reaction to form the sugar. Each photon must have a minimum amount of energy to drive the reactions.

The way plants harvest sunlight is a marvel of nature. Photosynthetic pigments such as chlorophyll are not isolated molecules. They operate in a network like an array of antennas, each tuned to pick out photons of particular wavelengths. Chlorophyll preferentially absorbs red and blue light, and carotenoid pigments (which produce the vibrant reds and yellows of fall foliage) pick up a slightly different shade of blue. All this energy gets funneled to a special chlorophyll molecule at a chemical reaction center, which splits water and releases oxygen.

The funneling process is the key to which colors the pigments select. The complex of molecules at the reaction center can perform chemical reactions only if it receives a red photon or the equivalent amount of energy in some other form. To take advantage of blue photons, the antenna pigments work in concert to convert the high energy (from blue photons) to a lower energy (redder), like a series of step-down transformers that reduces the 100,000 volts of electric power lines to the 120 or 240 volts of a wall outlet. The process begins when a blue photon hits a blue-absorbing pigment and energizes one of the electrons in the molecule. When that electron drops back down to its original state, it releases this energy—but because of energy losses to heat and vibrations, it releases less energy than it absorbed.

The pigment molecule releases its energy not in the form of another photon but in the form of an electrical interaction with another pigment molecule that is able to absorb energy at that lower level. This pigment, in turn, releases an even lower amount of energy, and so the process continues until the original blue photon energy has been downgraded to red. The array of pigments can also convert cyan, green or yellow to red. The reaction center, as the receiving end of the cascade, adapts to absorb the lowest-energy available photons. On our planet's surface, red photons are both the most abundant and the lowest energy within the visible spectrum.

For underwater photosynthesizers, red photons are not necessarily the most abundant. Light niches change with depth because of filtering of light by water, by dissolved substances and by overlying organisms themselves. The result is a clear stratification of life-forms according to their mix of pigments. Organisms in lower water layers have pigments adapted to absorb the light colors left over by the layers above. For instance, algae and cyanobacteria have pigments known as phycobilins that harvest green and yellow photons. Nonoxygen-producing (anoxygenic) bacteria have bacteriochlorophylls that absorb far-red and near-infrared light, which is all that penetrates to the murky depths.

Organisms adapted to low-light conditions tend to be slower-growing, because they have to put more effort into harvesting whatever light is available to them. At the planet's surface, where light is abundant, it would be disadvantageous for plants to manufacture extra pigments, so they are selective in their use of color. The same evolutionary principles would operate on other worlds.

Just as aquatic creatures have adapted to light filtered by water, land dwellers have adapted to light filtered by atmospheric gases. At the top of

[THE AUTHOR]

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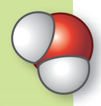
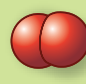
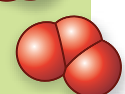
Biosignatures

Aside from colors reflected by plants, these other features could be signs of life:

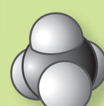


Oxygen (O_2) plus water (H_2O). Even on a lifeless world, light from the parent star naturally produces a small amount of oxygen in a planet's atmosphere by splitting water vapor. But the gas is quickly rained out, as well as consumed through oxidation of rocks and volcanic gases. Therefore, if a planet with liquid water has abundant oxygen, some additional source must be producing the gas. Oxygenic photosynthesis is the leading candidate.

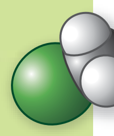




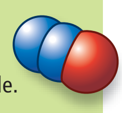
Ozone (O_3). In Earth's stratosphere, radiation splits apart oxygen, which then recombines to form ozone. Together with liquid water, ozone is a strong biosignature. Whereas oxygen can be detected at visible wavelengths, ozone can be detected at infrared wavelengths, which is easier for some telescopes.



Methane (CH_4) plus oxygen or seasonal cycles. Oxygen and methane are an awkward chemical combination that is hard to achieve without photosynthesis. A seasonal cycle of rising and falling methane concentrations is also a good sign of life. On a dead planet, methane levels are fairly constant, declining slightly over the long run as starlight splits the molecules.



Methyl chloride (CH_3Cl). On Earth this gas results from the burning of vegetation (mainly forest fires) and from the action of sunlight on plankton and seawater chlorine. Oxidation destroys it. But an M star's relatively weak radiation might allow the gas to build up to detectable amounts.



Nitrous oxide (N_2O). When plant matter decays, it releases nitrogen in the form of nitrous oxide. Abiotic sources of this gas, such as lightning, are negligible.

WALLACE ZANE (*Kiang*); LISA APFELBACHER (*molecules*)

Filtering Starlight

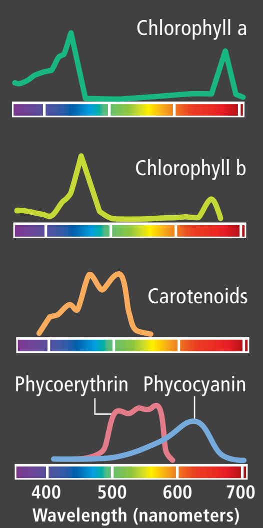
The color of plants depends on the spectrum of the star's light, which astronomers can easily observe, and filtering of light by air and water, which the author and her colleagues have simulated based on the likely atmospheric composition and life's own effects.

STAR TYPE: M (mature)
MASS*: 0.2
LUMINOSITY*: 0.0044
LIFETIME: 500 billion years
ORBIT OF MODELED PLANET: 0.07 astronomical unit
**Relative to sun*

STAR TYPE: M (young)
MASS*: 0.5
LUMINOSITY*: 0.023
LIFETIME: Flaring: 1 billion years
Total: 200 billion years
ORBIT OF MODELED PLANET: 0.16 astronomical unit

Photosynthetic pigments absorb different ranges of wavelengths. All land plants on Earth rely on chlorophyll a and b and a mixture of carotenoid pigments. Algae and cyanobacteria use phycobilin pigments.

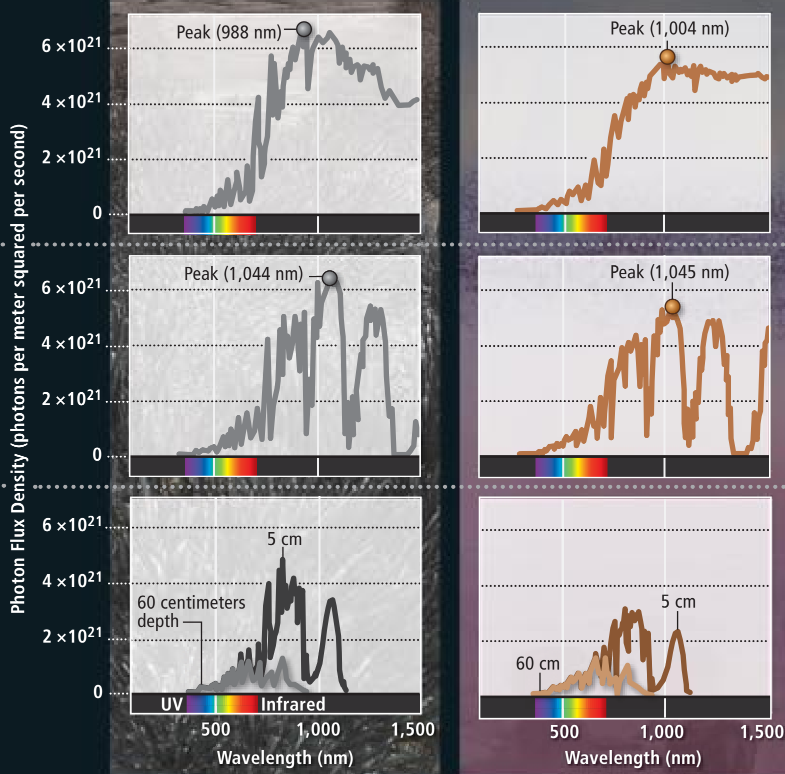
RELATIVE ABSORPTION



STARLIGHT
Before entering the atmosphere, starlight has a distinctive spectrum. The overall shape is determined by the surface temperature of the star, with a few dips produced by absorption in the star's own atmosphere.

SURFACE
Atmospheric gases absorb the starlight unevenly, shifting its peak color and introducing absorption bands—wavelengths that are screened out. These bands are best known for Earth (the G-star case).

UNDERWATER
Water tends to transmit blue light and absorb red and infrared light. The graphs shown here are for water depths of five and 60 centimeters. (The mature M-star case is for a low-oxygen atmosphere.)



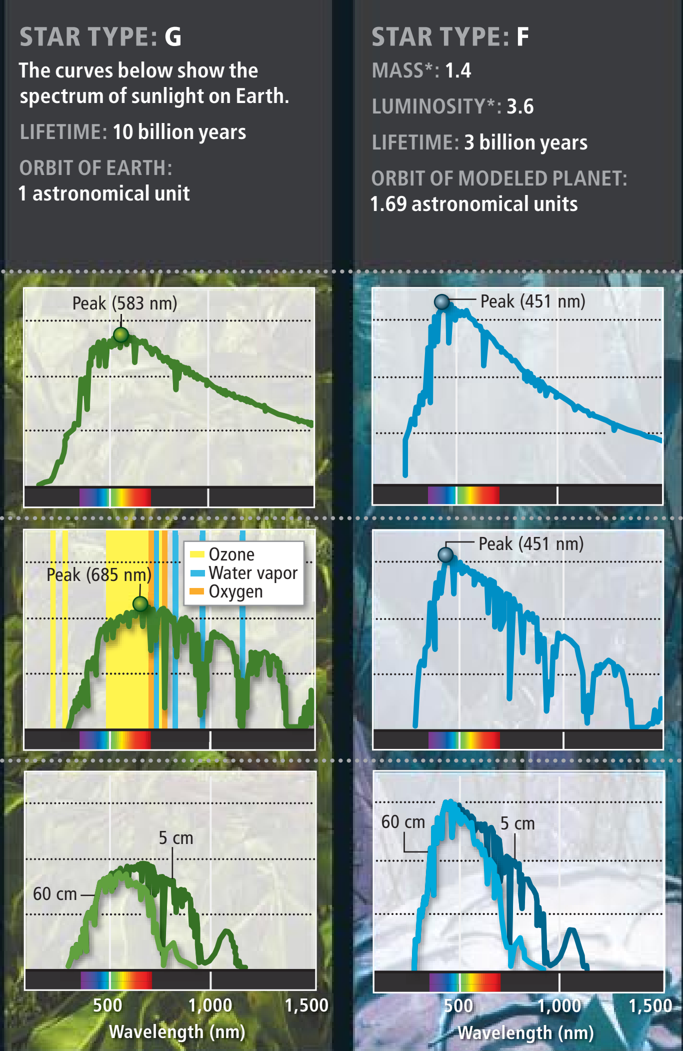
Earth's atmosphere, yellow photons (at wavelengths of 560 to 590 nanometers) are the most abundant kind. The number of photons drops off gradually with longer wavelength and steeply with shorter wavelength. As sunlight passes through the upper atmosphere, water vapor absorbs the infrared light in several wavelength ands beyond 700 nm. Oxygen produces absorption lines—narrow ranges of wavelengths that the gas blocks—at 687 and 761 nm. We all know that ozone (O_3) in the stratosphere strongly absorbs the ultraviolet (UV). Less well known is that it also absorbs weakly across the visible range.

Putting it all together, our atmosphere demarcates windows through which radiation can make it to the planet's surface. The visible radiation window is defined at its blue edge by the drop-off in the intensity of short-wavelength photons emitted by the sun and by ozone absorption of UV. The red edge is defined by oxygen absorption lines. The peak in photon abundance is shifted from yellow to red (about 685 nm) by ozone's broad absorbance across the visible.

Plants are adapted to this spectrum, which is determined largely by oxygen—yet plants are what put the oxygen into the atmosphere to begin with. When early photosynthetic organisms first appeared on Earth, the atmosphere lacked oxygen, so they must have used different pigments from chlorophyll. Only over time, as photosynthesis altered the atmospheric composition, did chlorophyll emerge as optimal.

The firm fossil evidence for photosynthesis dates to about 3.4 billion years ago (Ga), but earlier fossils exhibit signs of what could have been photosynthesis. Early photosynthesizers had to start out underwater, in part because water is a good solvent for biochemical reactions and in part because it provides protection against solar UV radiation—shielding that was essential in the absence of an atmospheric ozone layer. These earliest photosynthesizers were underwater bacteria that absorbed infrared photons. Their chemical reactions involved hydrogen, hydrogen sulfide or iron rather than water, so they did not produce oxygen gas. Oxygen-generating (oxy-

JEN CHRISTIANSEN



genic) photosynthesis by cyanobacteria in the oceans started 2.7 Ga. Oxygen levels and the ozone layer slowly built up, allowing red and brown algae to emerge. As shallower water became safe from UV, green algae evolved. They lacked phycobilins and were better adapted to the bright light in surface waters. Finally, plants descended from green algae emerged onto land—two billion years after oxygen had begun accumulating in the atmosphere.

And then the complexity of plant life exploded, from mosses and liverworts on the ground to vascular plants with tall canopies that capture more light and have special adaptations to particular climates. Conifer trees have conical crowns that capture light efficiently at high latitudes with low sun angles; shade-adapted plants have anthocyanin as a sunscreen against too much light. Green chlorophyll not only is well suited to the present composition of the atmosphere but also helps to sustain that composition—a virtuous cycle that keeps our planet green. It may be that another step of evolution will favor an organism that takes advantage of the shade underneath tree canopies, using the phycobilins that absorb green and yellow light. But the organisms on top are still likely to stay green.

Predicting alien plant colors takes experts ranging from astronomers to plant physiologists to biochemists.

Painting the World Red

To look for photosynthetic pigments on another planet in another solar system, astronomers must be prepared to see the planet at any of the possible stages in its evolution. For instance, they may catch sight of a planet that looks like our Earth two billion years ago. They must also allow that extrasolar photosynthesizers may have evolved capabilities that their counterparts here have not, such as splitting water using longer-wavelength photons.

The longest wavelength yet observed in photosynthesis on Earth is about 1,015 nm (in the infrared), in purple anoxygenic bacteria. The longest wavelength observed for oxygenic photosynthesis is about 720 nm, in a marine cyanobacterium. But the laws of physics set no strict upper limit. A large number of long-wavelength photons could achieve the same purpose as a few short-wavelength ones.

The limiting factor is not the feasibility of novel pigments but the light spectrum available at a planet's surface, which depends mainly on the star type. Astronomers classify stars based on color, which relates to temperature, size and longevity. Only certain types are long-lived enough to allow for complex life to evolve. These are, in order from hottest to coolest, F, G, K and M stars. Our sun is a G star. F stars are larger, burn brighter and bluer, and take a couple of billion years to use up their fuel. K and M stars are smaller, dimmer, redder and longer-lived.

Around each of these stars is a habitable zone, a range of orbits where planets can maintain a temperature that allows for liquid water. In our solar system, the habitable zone is a ring encompassing Earth's and Mars's orbits. For an F star, the habitable zone for an Earth-size planet is farther out; for a K or M star, closer in. A planet in the habitable zone of an F or K star receives about as much visible radiation as Earth does. Such a planet could easily support oxygenic photosynthesis like that on Earth. The pigment color may simply be shifted within the visible band.

M stars, also known as red dwarfs, are of special interest because they are the most abundant type in our galaxy. They emit much less visible radiation than our sun; their output peaks in the near-infrared. John Raven, a biologist at the University of Dundee in Scotland, and Ray Wolstencroft, an astronomer at the Royal Observatory, Edinburgh, have proposed that oxygenic photosynthesis is theoretically possible with near-infrared photons. An organism would have to use three or four near-infrared photons to split H_2O, rather than the two that suffice for Earth's plants. The photons work together like stages of a rocket to provide the necessary energy to an electron as it performs the chemical reactions.

M stars pose an extra challenge to life: when young, they emit strong UV flares. Organisms could avoid the damaging UV radiation deep underwater, but would they then be starved for light? If so, photosynthesis might not arise. As M stars age, though, they cease producing flares, at which point they give off even less UV radiation than our sun does. Organisms would not need a UV-absorbing ozone layer to protect them; they could thrive on land even if they did not produce oxygen.

In sum, astronomers must consider four scenarios depending on the age and type of star:

Anaerobic, ocean life. The parent star is a young star of any type. Organisms do not necessarily produce oxygen; the atmosphere may be mostly other gases such as methane.

Aerobic, ocean life. The parent star is an older star of any type. Enough time has elapsed for oxygenic photosynthesis to evolve and begin to build up atmospheric oxygen.

Aerobic, land life. The parent star is a mature star of any type. Plants cover the land. Life on Earth is now at this stage.

Anaerobic, land life. The star is a quiescent M star, so the UV radiation is negligible. Plants cover the land but may not produce oxygen.

Photosynthetic biosignatures for these different cases would clearly not be the same. From experience with satellite imagery of Earth, astronomers expect that any life in the ocean would be too sparsely distributed for telescopes to see. So the first two scenarios would not produce strong pigment biosignatures; life would reveal itself to us only by the atmospheric gases it produced. Therefore, researchers studying alien plant colors focus on land plants, either on planets around F, G and K stars with oxygenic photosynthesis or on planets around M stars with any type of photosynthesis.

Black Is the New Green

Regardless of the specific situation, photosynthetic pigments must still satisfy the same rules as on Earth: pigments tend to absorb photons that are either the most abundant, the shortest available wavelength (most energetic) or the longest available wavelength (where the reaction center absorbs). To tackle the question of how star type determines plant color, it took researchers from many disciplines to put together all the stellar, planetary and biological pieces.

Martin Cohen, a stellar astronomer at the University of California, Berkeley, collected data for an F star (sigma Bootis), a K star (epsilon Eridani), an actively flaring M star (AD Leo), and a hypothetical quiescent M star with a temperature of 3,100 kelvins. Antígona Segura, an astronomer at the National Autonomous University of Mexico, ran computer simulations of Earth-like planets in the habitable zone of these stars. Using models developed by Alexander Pavlov, now at the University of Arizona, and James Kasting of Pennsylvania State University, Segura studied the interaction between the stellar radiation and the atmosphere's likely constituents (assuming that volcanoes on these worlds emit the same gases they do on Earth) to deduce the planets' atmospheric chemistry, both for negligible oxygen and for Earth-like oxygen levels.

Using Segura's results, Giovanna Tinetti, a physicist at University College London, calculated the filtering of radiation by applying a

Plants on worlds around dim stars may need to harvest the full range of visible and infrared light. They might look black to our eyes.

DETAIL OF F-STAR FOLIAGE

KENN BROWN AND CHRIS WREN *Mondolithic Studios* model developed by David Crisp of the Jet Propulsion Laboratory in Pasadena, Calif. (This is one of the models enlisted to calculate how much light reaches the solar panels of the Mars rovers.) Interpreting these calculations required the combined knowledge of five of us: microbial biologist Janet Siefert of Rice University, biochemists Robert Blankenship of Washington University in St. Louis and Govindjee of the University of Illinois at Urbana-Champaign, planetary scientist Victoria Meadows of the University of Washington, and me, a biometeorologist at the NASA Goddard Institute for Space Studies.

We found that the photons reaching the surface of planets around F stars tend to be blue, with the greatest abundance at 451 nm. Around K stars, the peak is in the red at 667 nm, nearly the same as on Earth. Ozone plays a strong role, making the F starlight bluer than it otherwise would be and the K starlight redder. The useful radiation for photosynthesis would be in the visible range, as on Earth.

Thus, plants on both F- and K-star planets could have colors just like those on Earth but with subtle variations. For F stars, the flood of energetic blue photons is so intense that plants might need to reflect it using a screening pigment similar to anthocyanin, giving them a blue tint. Alternatively, plants might need to harvest only the blue, discarding the lower-quality green through red light. That would produce a distinctive blue edge in the spectrum of reflected light, which would stand out to telescope observers.

The range of M-star temperatures makes possible a very wide variation in alien plant colors. A planet around a quiescent M star would receive about half the energy that Earth receives from our sun. Although that is plenty for living things to harvest—about 60 times more than the minimum needed for shade-adapted Earth plants—most of the photons are near-infrared. Evolution might favor a greater variety of photosynthetic pigments to pick out the full range of visible and infrared light. With little light reflected, plants might even look black to our eyes.

Pale Purple Dot

The experience of life on Earth indicates that early ocean photosynthesizers on planets around F, G and K stars could survive the initial oxygen-free atmosphere and develop the oxygenic photosynthesis that would lead ultimately to land plants. For M stars, the situation is trickier. We calculated a "sweet spot" about nine meters underwater where early photosynthesizers could both survive UV flares and still have enough light to be productive. Although we might not see them through telescopes, these organisms could set the stage for life at the planet's surface. On worlds around M stars, land plants that exploited a wider range of colors would be nearly as productive as plants on Earth.

For all star types, an important question will be whether a planet's land area is large enough for upcoming space telescopes to see. The first generation of these telescopes will see the planet as a single dot; they will lack the resolution to make maps of the surface. All scientists will have is a globally averaged spectrum. Tinetti calculates that for land plants to show up in this spectrum, at least 20 percent of the surface must be land that is both covered in vegetation and free from clouds. On the other hand, oceanic photosynthesis releases more oxygen to the atmosphere. Therefore, the more prominent the pigment biosignature, the weaker the oxygen biosignature, and vice versa. Astronomers might see one or the other, but not both.

If a space telescope sees a dark band in a planet's reflected light spectrum at one of the predicted colors, then someone monitoring the observations from a computer may be the first person to see signs of life on another world. Other false interpretations have to be ruled out, of course, such as whether minerals could have the same signature. Right now we can identify a plausible palette of colors that indicate plant life on another planet; for instance, we predict another Earth to have green, yellow or orange plants. But it is currently hard to make finer predictions. On Earth, we have been able to determine that the signature of chlorophyll is unique to plants, which is why we can detect plants and ocean phytoplankton with satellites. We will have to figure out unique signatures of vegetation for other planets.

Finding life on other planets—abundant life, not just fossils or microbes eking out a meager living under extreme conditions—is a fast-approaching reality. Which stars shall we target, given there are so many out there? Will we be able to measure the spectra of M-star planets, which tend to be very close to their stars? What wavelength range and resolution do the new telescopes need? Our understanding of photosynthesis will be key to designing these missions and interpreting their data. Such questions drive a synthesis of the sciences in a way that is only beginning. Our very ability to search for life elsewhere in the universe ultimately requires our deepest understanding of life here on Earth. ■

PLANET FINDERS

The European Space Agency (ESA) plans to launch Darwin in about a decade to measure the spectra of Earth-size extrasolar planets. NASA's Terrestrial Planet Finder would do the same, when the agency can fund it. ESA's COROT, launched in December 2006, and NASA's Kepler, scheduled for 2009, seek the slight dimming caused by Earth-like planets as they pass in front of their stars. NASA's SIM PlanetQuest would look for a telltale wobbling of the star.

TERRESTRIAL PLANET FINDER

➡ MORE TO EXPLORE

Spectral Signatures of Photosynthesis II: Coevolution with Other Stars and the Atmosphere on Extrasolar Worlds. Nancy Y. Kiang, Antígona Segura, Giovanna Tinetti, Govindjee, Robert E. Blankenship, Martin Cohen, Janet Siefert, David Crisp and Victoria S. Meadows in *Astrobiology,* Special Issue on M Stars, Vol. 7, No. 1, pages 252–274; February 1, 2007. **http://pubs.giss.NASA.gov/docs/2007/2007_Kiang_etal_2.pdf**

Water Vapour in the Atmosphere of a Transiting Extrasolar Planet. Giovanna Tinetti, Alfred Vidal-Madjar, Mao-Chang Liang, Jean-Philippe Beaulieu, Yuk Yung, Sean Carey, Robert J. Barber, Jonathan Tennyson, Ignasi Ribas, Nicole Allard, Gilda E. Ballester, David K. Sing and Franck Selsis in *Nature,* Vol. 448, pages 169–171; July 12, 2007. **www.arxiv.org/abs/0707.3064**

Virtual Planetary Laboratory: **http://vpl.astro.washington.edu**

Astrobiology magazine: **www.astrobio.net**