NOVA Origins

Four-Part Television Series on PBS

Spectra Cart

An interactive cart developed by The Pacific Science Center as part of the educational outreach materials accompanying the *NOVA Origins Four-Part Television Series on PBS*, airing September 28 and 29, 2004

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Major contributors to the *NOVA Origins Four-Part Television Series on PBS* are:

Corporation for Public Broadcasting

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We would also like to thank the Space Telescope Science Institute for contributing materials, meeting space and many resources to the project.

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Welcome to *Spectra Cart*

An interactive science cart developed as part of the *NOVA Origins Four-Part Television Series on PBS*, airing September 28 and 29, 2004

The *Spectra Cart* was developed to give a fun, hands on introduction to HOW scientists know about things too distant in space to make direct observations by going there. The *Spectra Cart* allows participants to explore the properties of light such as reflection and refraction in a prism. Using scientific tools such as diffraction gratings and their own eyes, they discover emission spectra lines "hidden" in the light from an excited gas. Participants learn how to identify a "mystery gas" by studying the emission spectra and matching it to known gasses. The audience is left with an understanding that we can learn much from the information hidden in light, and is challenged to use their own "light decoders" (eyes) to learn about the cosmos. Perhaps someday that information may help discover another Earth-like planet or answer the question, "Are we alone in the universe?"

Target Audience: 4th–8th grade, but enjoyable for ages 7-adult.

Number of Participants: designed for an interactive experience with a presenter for 1-6 people at a time.

Spectra Cart has been successfully tested in a science-museum setting, classrooms, and at community-center after-school programs. The components of this demonstration are designed to be easily portable in a small vehicle.

The *Spectra Cart* was developed for the *NOVA Origins Four Part Television Series on PBS* and will be used to make people aware of the series prior to the air date. Because it focuses broadly on well established science, it is designed to continue to be used for years after the air date of the television series.

Concepts:

1. Visible light may be divided into the component wavelengths (colors) of the light, called its spectra.
2. Information may be obtained from spectra such as the composition of a gas.

Objectives:

Participants will:

1. discover that white light is a combination of different wavelengths (colors).
2. determine the composition of low density gases by their unique spectra.

Content Standard A: *Science as inquiry*

Science as Inquiry: Students use tools such as prisms to discover principles of light and diffraction grating to analyze differences in gas emission spectra.

Content Standard B: *Physical science*

Physical Science: Light interacts with matter by transmission (including refraction), absorption, or scattering (including reflection). To see an object, light from that object—emitted by or scattered from it—must enter the eye.

Content Standard G: History and nature of science

Science is a human endeavor that is open to all races, genders and abilities. This cart will give a wide variety of participants a chance to use tools of science including diffraction grating to examine properties of light. It is intended that the participants be left with a feeling that the science underlying how scientists learn from light is based on much experimental and observational confirmation. The main ideas are not likely to change greatly in the future, but there is room for refinement in principle as new discoveries are made. Perhaps a participant will be inspired to make some of those new discoveries.

A cart provides an opportunity for a participant to have a one-on-one interaction with a presenter. The presenter guides the participant's observations but does not dictate them. Each time the cart is presented will be unique, based on the participant's understandings and interactions. As such, there is no script.

Instead, we have provided an outline form showing the order in which concepts are typically best be presented to the participant in order to guide his/her observations.

Following the outline is a list of extensions that may be used to address other interests expressed by participants or to extend the experience of particularly interested people. Extensions are also wonderful attention getters to draw new participants to the cart.

The outline and extensions are provided as an example of one way the information has been successfully presented. Your organization may have other resources that it would like to add. Consider this a guideline for evolving your own cart, specific to the needs and skills of your organization.

A wide space has been intentionally left on the right side of the page for margin notes.

Materials

- ☐ Background materials
- ☐ White light with straight filament on dimmer switch
- ☐ Power strip
- ☐ Prism
- ☐ Spectrum poster
- ☐ Diffraction grating cards
- ☐ Two table-top spectral-tube power supplies
- ☐ Protective carrying case for spectral tubes
- ☐ Gloves for handling spectral tubes
- ☐ Seven gas-spectra tubes
  - ☐ Helium (two)
  - ☐ Water vapor
  - ☐ Oxygen
  - ☐ Air
  - ☐ Nitrogen
  - ☐ Hydrogen

Working with a prism

- Top of cart has diffraction grating glasses, white light source on dimmer, prism and a spectrum-tube power supply with one tube inserted so that the label for the tube faces away from view.
- Shelves of cart (unseen by public) hold additional spectrum tubes, a second spectrum tube power supply, spectra analysis chart, and background material.
- Presenter invites participant to "play" with prism. Participant is directed to rotate prism between participant's eyes and the white light and describe what he/she sees. Participant will see a variety of effects, including reflection of light, alteration of images, and bending of light that creates continuous spectrum (or "rainbow").
- Presenter discusses with participant nature of light and how we interpret light to learn about our environment.
- Presenter and participant discuss the fact that prisms bend light so the different energies (colors) of light are seen separately.

Working with diffraction-grating glasses and gas tubes

- Presenter gives participant diffraction-grating glasses and explains that the plastic in the glasses acts in a similar way to the prism.
- Presenter turns on white light power supply, making the element glow at various temperatures/colors.
- Participant is asked to describe what he/she sees through diffraction glasses.
- Participant will discover that when the element is just warm enough to emit light, the element is red. The spectrum is continuous, but the blue end of the spectrum is dim. As the heat of the element is increased, the element glows orange, then yellow and then white. The blue end of the spectrum becomes more apparent.
- Presenter describes how a similar process is used to tell the temperature of stars at great distances from Earth.
- Presenter then explains that the tube in the spectrum power supply contains a low density gas and turns on the power supply of the "mystery gas." Participant views gas through diffraction glasses and describes bright-line emission spectrum for the gas.
- Presenter explains how the spectrum of each gas is like a fingerprint that allows us to identify the gas in each tube. Presenter challenges the participant to determine the gas by comparing its emission spectrum to the emission spectra of various gases. Presenter stacks the power supplies vertically so that "mystery tube" and "comparison tube" line up vertically. This allows for the emission spectra to appear "stacked" horizontally for easy comparison.

- When "mystery gas" has been identified, participant can then compare water to hydrogen, and compare air to nitrogen and oxygen.
- Advanced participants may discuss how absorption spectra help determine the composition of gases in stars and how shifts in where spectral lines appear help determine speed at which bodies emitting light are moving toward or away from us.

Space is, well... BIG. Our deepest plunge into outer space has barely gotten us out of our own solar neighborhood. The closest star, Proxima Centauri, is about 4.2 light years away. If we sent a space craft 75,000 miles per hour to that closest star, it would take about 37,000 years to arrive. Average funding for a project would likely run out by then!

Because of the vast distances involved, we are unable to send space craft to extra-solar planets using any foreseeable technology. Instead, we must gather our information about the universe by decoding information from something much faster (and cheaper) than a spacecraft...light.

Light is a powerful tool, and vital to most of us for aid in navigation around and learning about our world. Yet most of us are in the dark about what light is, where it comes from, and how we can use it to gather information about our environment. For instance, ask yourself this question: "Can I see the paper on which these words appear?" The surprising answer is, actually, "No." Your eyes did not evolve the ability to detect and decode the light emitted from this page. (We will enlighten you later as to why this is true.)

Light Decoders explores how scientists unlock the secrets of light to learn about objects in space far too distant for us to physically travel. During the demonstration, participants use their own highly tuned scientific instruments, "Enhancers Yielding Electromagnetic Sensations" (EYES) to decode light. They learn how to tell the temperature of stars through blackbody radiation and how to tell the composition of a diffuse gas in space (such as a nebula or the atmosphere of a planet) by studying its emission spectra.

This topic has filled many physics and astronomy text books. Much chalk has been turned to dust working out equations on blackboards. This overview is not intended to give the full depth of this topic, but to provide enough information to spark the curiosity of the demonstrator and answer most of the questions that the kid in the front row with his/her hand constantly raised is likely to ask.

What is light?

In short, light is energy. Specifically, light is electromagnetic energy.

Electricity and magnetism have long had an intimate relationship. Many of us may remember wrapping a wire around a nail and letting electric current flow through the wire, causing the nail to become an electromagnet. The electric charge in motion created a magnetic field in the nail. As long as the current was flowing, the nail would be magnetized.

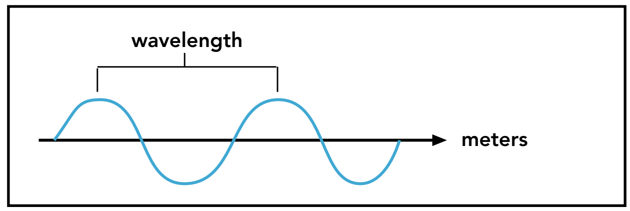
Experiments by James Clerk Maxwell in the mid-1800s shed even more light on the relationship between electricity and magnetism. He showed that not only do electric charges in motion cause magnetic fields, but that magnetic fields could create electric charges. He further showed that if the electric charges were oscillating, they would cause a wave pattern of self-triggering disturbance that would radiate throughout space. This is electromagnetic radiation. This electromagnetic radiation traveled at light speed and was soon determined to actually be "light."

Just as waves of water may be sorted by their wavelength—the distance between incoming waves—electromagnetic waves may also be categorized by their wavelength. Everyone is familiar with the seven colors of visible light in a rainbow: red, orange, yellow, green, blue, indigo, and violet. But visible light is only one of seven recognized categories of light waves! And just as a ripple and a tsunami carry differing amounts of energy and have quite differing effects, waves of light also have a range of effects depending on their length. Some light waves stimulate our eyes to perceive color. Other waves of light could knock around our atoms and cause painful death.

***Wavelength** is the distance between the crest of one wave and the crest of the next wave.*

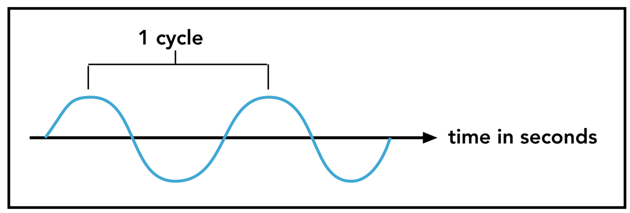
Light waves may be categorized according to their wavelength or by their frequency:

Wavelength



The wavelength is quite simply the distance between the crest of one wave and the crest of the next wave. Some low-energy waves only repeat once every kilometer. Other, very high-energy waves are measured in nanometers or billionths of a meter.

Frequency



Frequency is the number of times the wave pattern repeats over a period of time. This is usually measured in cycles per second, or hertz. The higher the energy of the wave, the more frequently the wave pattern will repeat in a second.

***Frequency** is the number of times the wave pattern repeats over a period of time.*

Because all types of light travel at the same speed, there is a direct relationship between a wave's wavelength and its frequency. A low-energy wave will have a low frequency and long wavelength. A high-energy wave will have a high frequency and short wavelength.

The frequencies, in order from longest wavelength (lowest frequency) to shortest wavelength (highest frequency), are:

- Radio waves (the kind used to transmit from the radio station to your radio antenna; this is NOT the type of wave that carries the sound from the speakers to your ears) are about the size of mountains.
- Microwaves (cooking with light!) are between human size and insect size.
- Infrared waves (We can't SEE infrared, but we can sense it as heat) are around the size of pinpoints.
- Visible-light waves are about the size of single-celled organisms:
    - Red (lowest-frequency visible light, longest wavelength)
    - Orange
    - Yellow

    - Green
    - Blue
    - Indigo
    - Violet (highest-frequency visible light, shortest wavelength)
- Ultraviolet waves (the kind that gives you sunburn and can damage your eyes if look directly at the sun). These are about the size of molecules.
- X-ray waves (the same ones used to look at bones through skin and soft tissue). These are about the size of atoms.
- Gamma-ray waves (super-high-frequency wavelengths that would cause major harm if the Earth's atmosphere and magnetic fields didn't shield us from them; no, they probably would not actually turn Bill Bixby into the Incredible Hulk). Gamma wavelength is about the size of atomic nuclei.

The human eye has evolved to be sensitive to only a small fraction of the entire spectrum of the possible electromagnetic frequencies. This is probably a good thing. Remember that electromagnetic radiation is caused by charged particles in motion. Atoms are made up of charged particles and any atom above 0 degrees Kelvin is in motion... pretty much everything creates electromagnetic radiation! If our eyes were sensitive to the full spectrum of radiation, we would have too much information for any of it to be useful.

Instead, our eyes are adapted to be sensitive to the specific range of wavelengths most crucial for our survival under this planet's conditions. The most common wavelengths of light that our star, the sun, emits are between 700 nanometers (red) and 400 nanometers (blue). The sun does emit some of all of the other types of light waves as well. Our atmosphere blocks many of them, such as most microwaves, some infrared waves, most ultraviolet waves, and x-rays. Our magnetic field shields us from the high-energy gamma rays.

Human eyes have evolved special cells which are sensitive to red, green and blue wavelengths of light. This allows us to decode the most common light waves emitted from our sun. If we detect the full range of wavelengths all at once, from red through violet, our brains interpret this light as "white." If we don't detect light in these wavelengths, our brain interprets this as "black."

Emitted, absorbed or reflected

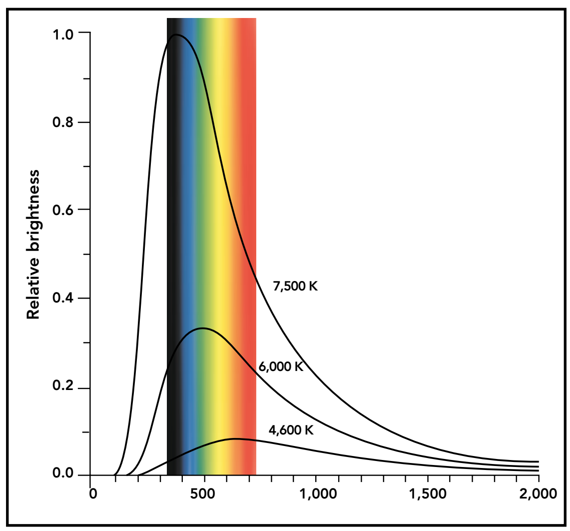
When we walk outside on the surface of our planet, we see the sun's light reflecting from objects. If we look at a parking lot we can't actually see the energy the atoms in the pavement are emitting. Our eyes are not adapted to see frequencies that low. We can only detect the sun's reflected light. The sun's "white" light (all of the visible wavelengths of light mixed together) shine on the parking lot. Many of the wavelengths of light are absorbed by the black pavement and few are reflected. That is why the pavement looks mostly "black". The white paint forming the lines of the parking spots reflects most of the energies of light and relatively little of the visible light is absorbed. That's why it appears white to our eyes. Our eyes detect the energy that was reflected and not absorbed. You can test this theory with your bare feet—on a sunny day, the black pavement will be much more energetic or "hotter" than the white paint.

This is why you can't actually see the paper in your hands... or even your hands for that matter. You can only detect the reflected wavelengths of light from the paper. You truly can't see your hand in front of your face. If a police officer asks "How many fingers do you see?," you may very knowledgeably answer, "None. You don't emit enough energy in visible light for me to actually see you. I can only see light reflected from your fingers. As a matter of fact, you can't see me either." The statement would be true, but we don't actually recommend that answer.

Hot light and color — in case you incandesce...

There is a relationship between a solid object's emitted color and the object's temperature. Remember that emitted color is different than reflected color. Temperature is a measurement of motion in the atoms. The more motion, the higher the temperature. The higher the temperature, the more higher-frequency light will be emitted. In dense objects, where the atoms are relatively close together, there's a direct relationship between the object's temperature and the energy of the light (color) that the object is emitting.

For instance, picture the metal burner on an electric range. Even when the burner is off, the atoms in the burner are moving and colliding. The burner is giving off electromagnetic radiation, but the average frequency is too small for us to sense. As we add energy to the burner, the atoms move more and begin to emit electromagnetic energy that we can sense—infrared radiation (heat). As we continue to add energy to the burner, the average motion of atoms (temperature) in the burner rises. More infrared energy is emitted, plus more of the higher-energy red wavelengths are emitted. As we add more energy, even more infrared and red wavelengths are emitted, plus the object will emit more orange wavelengths. If enough energy is added to the burner element so the average motion of the atoms emits mainly orange light, then the burner appears orange to our human eyes. When the burner appears orange, it is still emitting infrared radiation, red radiation, and even some higher frequencies such as yellow, because the specific atoms in the burner are moving a differing speeds. The average motion, however, produces mainly orange light.



This blackbody radiation curve shows how much energy the star is emitting at each wavelength. The blue star (7000 K) emits more energy at each wavelength than do the other stars.

Stars operate in much the same way. We can gauge the temperature of a star based on its radiation curve. Stars will give off all wavelengths of visible light, but a relatively cooler star (about 4000K) would appear reddish. A hotter star, about 5000K, would appear yellow. An object 7,500 Kelvin would appear blue even though it is emitting more red, yellow, green, etc., light than the cooler stars.

A star that peaks in the green would actually appear white to our eyes. This makes sense when you consider that green is the middle range of visible wavelengths and "white" light is the mixture of all visible waves. Thus, the visual order of an object emitting light is red, orange, yellow, white, blue.

Emitted color gives astronomers a relative scale of temperature from hot, dense bodies, such as a star. We know that emitted blue light is a higher frequency and therefore relatively hotter than red. Some especially hot stars will even average in the ultraviolet. Astronomers can measure the amount of energy given off at each wavelength to determine the numeric temperature of the star.

Cool light, or fluorescence

We just covered how energy in a dense object (such as the metal in a burner or a star) can effect the light energy it emits. The laws of physics that work with less dense objects such as diffuse gases in space are a bit different. Diffuse gas can emit light without as much heat. We have experience with this in lighting fixtures. An incandescent light bulb with a metal filament gives off about 97 percent of its energy as heat and only 3 percent as visible light. If an incandescent bulb is on for some time, it will feel very hot. A florescent bulb, which uses light emitted from excited gases, will not give off as much heat. It will still feel relatively cool after operation compared to an incandescent bulb. To understand how this works, we need to take a quick tour of an atom.

The smallest elemental building block is an atom. By "small," we mean that one gram of a substance may contain over 1,000,000,000,000,000,000,000 atoms. An atom has three types of subatomic particles: positively charged protons, neutrally charged neutrons, and negatively charged electrons. The number of protons in the nucleus defines the atom. For instance, hydrogen has one proton in its nucleus. Helium has two. Carbon has six. Uranium has 92 protons. (This corresponds to a substance's atomic number listed on the periodic table of the elements.) Protons and neutrons have nearly equal mass. Electrons are much smaller, about 1/1835th the mass of protons.

Protons and neutrons are together in the center, or nucleus, of the atom. Electrons orbit outside the nucleus. Most of an atom is empty space. Imagine if a carbon atom in your fingernail were the size of a very large room. The nucleus of protons and neutrons would be about the size of a ball bearing. The rest of the atom would be empty space with electrons around the edge of the room, (far too small to see) moving in orbits around the nucleus.

Protons have a positive electric charge. Electrons have a negative electrical charge. Most atoms have the same number of electrons as protons so the charges balance out. However, since opposite charges attract, why don't the electrons plunge into the nucleus of the atom as differently charged magnets would? Each electron in an atom has a certain specific amount of energy that keeps it in motion, orbiting at a specific distance from the nucleus known as that electron's energy level. You might imagine this as the "flight pattern" of an electron. It is possible for an electron to "jump up" to a different flight pattern that requires more energy.

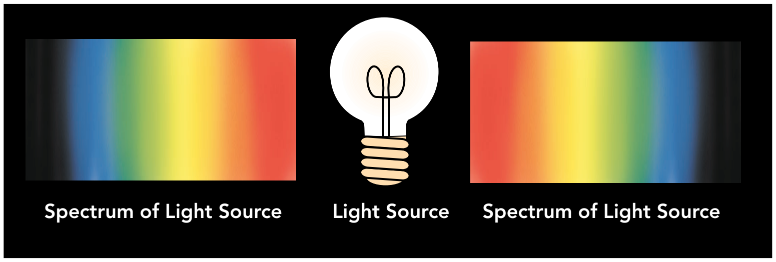
If energy is added to an atom, the energy may be temporarily "stored" in that atom by pushing the electrons to higher energy levels for a period of time. When the electrons "fall back" to their normal energy levels (flight paths) they give off this extra energy, which scientists call fluorescence. This extra packet of energy given off is called a photon. A photon has a certain specific frequency (color) of energy.

Since each element has a specific number electrons in specific "flight paths" or energy levels around the nucleus, the way in which that element gives off photons of light energy will be unique. This can be used to identify the element. If we use a tool that can detect how many photons are being given off at specific energies, we can determine the element in the gas. The equipment used by astronomers measures very specific wavelengths in order to determine the exact composition of a gas in space. We can do a similar thing using our own specialized scientific tools, our "Enhancers Yielding Electromagnetic Sensations" (EYES) plus a diffraction grating.

Diffraction grating

Diffraction grating is a specialized film with thousands of parallel scratches per millimeter. These scratches have a very precise spacing that cause waves of light energy to interfere with each other. When waves interfere in a way that cancels each other out, we observe darkness. When waves interfere in a constructive manner, we see intense patterns of color displaced to the side of the light source. We call this the spectrum of the light source.

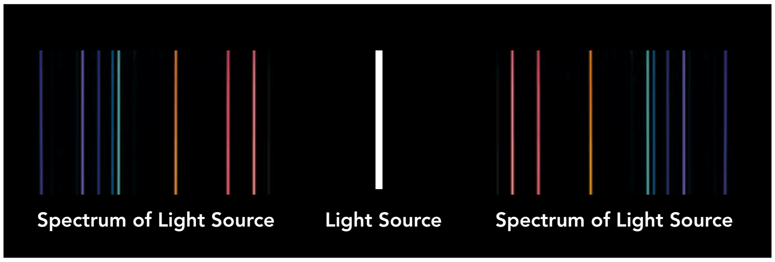
A white light (such as an incandescent light or sunlight) will appear as in this illustration



A white light (such as an incandescent light or sunlight) will appear as in the illustration above. The high-energy, shorter wavelength light (blue) is displaced the least and the longer wavelength (red) is displaced the most so the blue side of the spectrum will be closest to the light source. Since a "white" light is the combination of all visible wavelengths of light, we see all the colors (red, orange, yellow, green, blue, indigo, violet). The hotter the incandescent light, the more apparent the blue end of the spectrum will appear.

If we pass light emitted by a fluorescent through diffraction grating, we can see a pattern similar to this.

What if the source light is NOT white light? Let's use a florescent source such as excited helium. Remember that an excited gas only gives off energy at certain specific wavelengths. If we pass this light through diffraction grating, we can see a pattern similar to this *(at right).*



The light in the middle is florescent light from excited helium gas. Note that the higher energy, shorter wavelengths (blue side) are closer to the source light and the longer wavelengths (red side) are farther away just as in the incandescent light spectrum.

The specific energies (or colors) of light emitted by the excited helium gas relate to how its electrons emit photons. This pattern is unique for each gas. It works as a "spectral fingerprint."

The big hint!!!

Remember

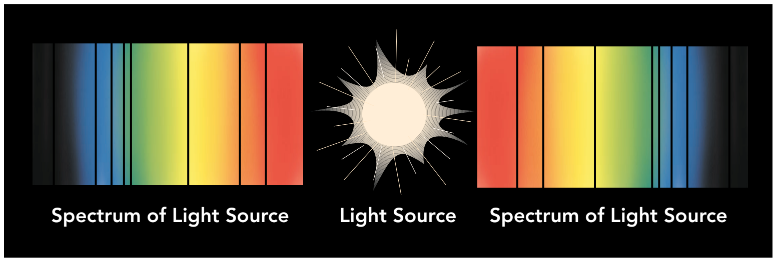
- The color something reflects is different than the color it emits. Reflecting red is not the same as emitting red.
- Incandescence is different than fluorescence. An object with atoms close together will give off incandescent light as it heats up. We can tell how hot an object is by its emitted incandescent color.
- Fluorescent color does not directly indicate the object's temperature. When a gas fluoresces, the atoms absorb energy by knocking specific electrons to higher energy levels. When the electrons fall back, they give off specific wavelengths of energy. We can detect the specific wavelengths of light from a gas and identify the element by its unique "spectral fingerprint.

A bit further

If a star is composed of gases so dense that they act as a "blackbody" incandescent light, then how can astronomers know what stars are made of?

Stars have atmospheres of less dense gas that surround them. This cool gas will absorb light at the same specific frequencies as an excited gas will emit light. So, when the full spectra light from the dense parts of the sun go through the atmosphere surrounding the sun, light is absorbed at specific frequencies. In this way, scientists can know the composition of the atmosphere of a star by what light is NOT there.

This oversimplified illustration shows the absorption of helium in the atmosphere of the sun. In reality, the sun's spectra would have over 100,000 absorption lines.



The same basic principal would hold true of light from a star being reflected from a planet through that planet's atmosphere. The atmosphere of a planet would absorb light at specific frequencies and would thus allow scientists to know the composition of that planet's atmosphere at a great distance.

Indicators of life

If there is life "out there," other than on our tiny planet orbiting a rather average star in an unremarkable arm of a common spiral galaxy, how will we ever recognize it? Today our best way of knowing is to decode information hidden in light. We have satellites that monitor light in all frequencies from radio waves to gamma radiation. We can use this information to find areas in space the right distances from stars where planets could be the right temperature to have liquid water. In the future, we may also look at the spectral signature of the atmosphere of these planets. Perhaps there will be a "biomarker" indicating that life may exist on that planet. What would that marker be? Methane? Free oxygen? Chlorophyll?

At the time of this writing, we don't have the technology to image a planet farther away than our solar neighborhood. However, in the near future, NASA plans missions to specifically search for planets. The first mission is currently scheduled for 2012.

This means that many of the middle-school students who see this demonstration will be graduating from college about the time these missions will take place. Perhaps one of these students will be the first to find signs of life on another planet.

Diffraction Grating

Learning Technologies, Inc.
40 Cameron Avenue
Somerville, Massachusetts 02144 U.S.A.
Phone: 1 (800) 537-8703 (U.S. only) or 1 (617) 628-1459
Fax: 1 (617) 628-8606
http://www.starlab.com/psprod.html

Spectrum tubes, power supplies, prisms:

Kelvin
280 Adams Boulevard
Farmingdale, NY 11735
1 (631) 756-1750
www.kelvin.com

Ward's Natural Science
PO Box 92912
Rochester, NY
1 (692) 9012
1 (800) 962-2660

Carolina Biological Supply Company
PO Box 60232
Charlotte, NC 28260-0232
1 (336) 584-0381
www2.carolina.com

Frey Scientific
P.O. Box 8101
100 Paragon Parkway
Mansfield, OH 44903
1 (800) 225-FREY
http://www.freyscientific.com

Web links

Electromagnetic Spectrum

http://www.pbs.org/wgbh/nova/gamma/spectrum.html
http://www.lhsgems.org/IUtour.html
http://irastro.jpl.nasa.gov//index.html

Emission spectra

http://curious.astro.cornell.edu/question.php?number=298
http://mhhe.com/physsci/astronomy/arny/instructor/graphics/ch03/0312.html
http://www.regentsprep.org/Regents/physics/phys05/cspectrum/default.htm
http://www.astronomy.ohio-state.edu/~pogge/Ast162/Intro/Spectra/index.html

Evolution of stars

http://www.milky-way.com/gb/sevol.htm
http://www.sr.bham.ac.uk/xmm/intro3.html

Orion nebula and stars

http://www.stormpages.com/swadhwa/stellarevolution/lecture13.htm
http://www.astro.uiuc.edu/~kaler/sow/bellatrix.html
http://www.astro.uiuc.edu/~kaler/sow/betelgeuse.html
http://www.astro.uiuc.edu/~kaler/sow/rigel.html

Stellar spectra

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http://lheawww.gsfc.nasa.gov/users/allen/spectral_classification.html
http://home.achilles.net/~jtalbot/data/stars/
http://www.learner.org/teacherslab/science/light/color/spectra/index.html
http://www.gettysburg.edu/academics/physics/clea/speclab.html
http://zebu.uoregon.edu/~soper/Stars/color.html

Images of the sun

http://www.nineplanets.org/pxsol.html