Exploring the Invisible Frontier

Why Astronomers Observe in Infrared

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Exploring the Invisible Frontier: Why Astronomers Observe in Infrared

When the Hubble Space Telescope's successor goes into orbit in the next decade, it won't detect light visible to the human eye; instead, it will be looking at infrared wavelengths. When the first phase of the Terrestrial Planet Finder is launched a few years later, it too will scan the skies in infrared. Even the largest telescopes being built today are optimized not for light we can see, but for the mysterious form of radiation we call "infrared." Why are astronomers interested in this kind of light?

Infrared observations may help us answer some of astronomy's greatest questions. What was the Universe like in its earliest history? How did the elements to make life come into existence? How do planets form? Are there planets like Earth orbiting other stars? Astronomers are searching for important clues at infrared wavelengths.

Infrared Background

Let's back up a step. "Infrared"? "Wavelengths"? What are we talking about when we use these terms?

The first thing that comes to mind for most people when they hear "infrared" may be night-vision goggles, cameras used by firefighters, or surveillance tools. Many such devices indeed detect infrared light, mostly because the human body radiates in infrared light all the time—we may not be able to see it, but we're glowing in infrared!

Simply put, the human eye sees electromagnetic radiation, what we commonly call "light." But we see only a tiny fraction of the entire electromagnetic spectrum (Figure 1), of all the light that's zinging around the

Universe—or even around each one of us. We can build instruments to observe many other kinds of light, and technological advances in cameras and detectors have dramatically changed our perspective on the Universe. Astronomers know as much as they do by studying many forms of light, including infrared.

Astronomers prefer to deal with the exactitude of numbers over the ambiguities of other terms, so they characterize light by its "wavelength," the distance between points when the wave's electric and magnetic fields are in the same phase (Figure 2). Fundamentally, many of the same equations that describe waves in the ocean or sound waves in the air also describe the behavior of light. Instead of describing the motion of molecules in air or water, however, the equations describe changing electric and magnetic fields—rather abstract quantities that allow astronomers to understand light's properties and behavior.

Light carries energy, and the wavelength of light is inversely proportional to the energy it carries—which is to say that longer-wavelength light carries less energy than shorter-wavelength light. Red light carries less energy than yellow light, yellow light less than green, green less than blue, blue less than violet, and so on.

Infrared light lies beyond the visible spectrum, at wavelengths longer than the red light we see—literally infra- (meaning "below") red. At even longer wavelengths, we find microwaves and radio waves: the wavelengths of light we use to cook food and send music and talk shows across country! Using long-wavelength, low-energy light to get these jobs done makes sense because, among other things, it takes relatively little energy.

On the opposite side of the visible spectrum, at wavelengths a little shorter than violet light, we have ultra- (meaning "beyond") violet radiation, the stuff you shield your eyes and your skin from when you go outside on a sunny day. X-rays and gamma rays have even shorter wavelengths, which means they can do some damage to our bodies' cells and DNA. Shorter wavelengths of light carry more energy, which is what makes them potentially dangerous.

Unlike waves in water or air, however, light can travel in a vacuum: a scientist would say that light does not require a medium in which to propagate. That means light can travel across the vast distances of space, to be collected by our telescopes on Earth. Even after making such a lengthy journey, the light can still tell us something about where it originated, and that's why astronomers invest their time in constructing ever larger and more sensitive instruments—to collect fainter and fainter light signals from the distant reaches of the Universe.

Why Infrared?

With all these wavelengths to choose from, why are astronomers so interested in infrared light? In part, it's because many interesting astronomical objects shine in infrared, but also because some of the tools astronomers use work well in infrared.

To understand why astronomers study particular kinds of light, it's important to think about how light behaves. In very basic terms, light can be emitted, or it can be absorbed, reflected, or scattered. Scientists observe other behaviors of light as well, but we can understand many of the astronomical reasons for studying infrared just by considering just two of these processes: scattering and emission.

In the everyday world, most of the light we see around us is reflected—off the page of a magazine, for example, or off your clothing or skin. But light also gets scattered into our eyes—most spectacularly by molecules in our atmosphere, making the sky blue (we'll get back to that in greater detail). An additional bit of light we see is actually emitted by a light source—such as a light bulb, a computer screen, or the Sun.

As it turns out, one of the primary ways in which an object emits light is related to its temperature. That's why we can use special cameras to spot people in smoky rooms or on dusty battlefields—because the human body emits light. A hot object, such as the Sun, emits its peak wavelengths in light that we can see, but a cooler object, such as a person, emits most of its light in much longer (less energetic) wavelengths, namely in infrared.

Even cooler than stars or human bodies are disks of dust that surround stars, clouds of gas in interstellar space, and planets themselves. Since we can't see the light such objects emit with our unaided eyes, we need to look in infrared light if we want to take a picture of them. You can see this in images of the galaxy M81 (Figure 3), an enormous system of stars, gas, and dust comparable to our own Milky Way Galaxy.

All light is emitted from some source at some point, but many things can happen to a light wave once it gets emitted. Space is fairly empty (a better vacuum than the best vacuum on Earth), but light travels considerable distances in space, and it can eventually encounter atoms or molecules or dust grains that will absorb, reflect, or scatter the light, changing its direction.

Absorption, reflection, and scattering result each do different things to a light wave. We'll focus on scattering. Even the term "scattering" in physics refers to several different processes: in astronomy, "scattering" usually refers to Rayleigh scattering, which occurs when atoms, molecules, or dust particles cause light waves to fly off in random directions. Light coming in from one direction will get scattered in all directions, and the longer the wavelength of light, the more likely it is to get its direction randomized by this process.

We don't think of scattered light much in the day-to-day world, but it's responsible for some familiar phenomena. Shorter wavelengths scatter more easily than longer wavelengths. Thus, the sky looks blue because blue's shorter wavelengths get knocked around in Earth's atmosphere to such a degree that the atmosphere takes on a nearly uniform blue tint. And the sun looks reddish at sunset because, if we look directly at its disk, we're seeing the blue (scattered) light subtracted out, leaving the longer-wavelength red light. In other words, the sky looks blue because we see sunlight scattered into our eyes from molecules in our atmosphere; the setting sun looks red because most of the blue light it emits is scattered away—making the sky blue elsewhere.

A star's peak emission may be in visible light, but it nonetheless emits some light in the infrared part of the spectrum, too. If a cloud of thick dust gets in the way of seeing the star—an astronomer would say that the cloud lies in the "line of sight" of the star—it can block much of the star's visible light. But longer wavelengths don't scatter as much as shorter wavelengths, so some of the infrared light seeps through. We see this in many clusters of young stars (see Figure 4). As it turns out, dust is an important by-product of star formation, so we often see young, newly-born stars shrouded in thick dust. If we only observe at visible wavelengths, we don't see all of the stars; instead, we see the dust and glowing gas that hides the stars from view. By looking at infrared images of young star clusters, we see many more stars, otherwise concealed by their dusty environment.

Thanks to the most basic physics, infrared astronomy offers significant benefits: interesting objects (interstellar clouds, dusty disks, and planets, among other things) emit infrared light, and infrared light, because of its longer wavelength is subject to less degradation (in the form of scattering) than light we can see. But astronomers have even more reasons to focus on infrared astronomy.

One Last Subtlety

One more reason for studying infrared light hasn't been touched on yet: it has to do with the expansion of the Universe.

Less than a century ago, the astronomer Edwin Hubble (for whom the famous space-based telescope was named) discovered that the Universe is expanding. Virtually every galaxy he studied appeared to be moving away from Earth; furthermore, the more distant galaxies were speeding away faster than galaxies nearer by.

Hubble determined the speed with which a particular galaxy was moving away by studying the "redshift" of light emitted by stars in the galaxy. In a process known as the "Doppler shift," wavelengths of light get shifted toward longer (redder) wavelengths when a light-emitting object is moving away from an observer. (If the light-emitting object is moving toward us, we see the light shifted toward shorter wavelengths, or, you guessed it, "blueshifted.") In the everyday world, we witness this phenomenon with sound waves. If you've ever been standing on a street when an ambulance speeds by with its siren blaring, you may have noticed that the pitch of the siren changes when the ambulance passes by you. When it's coming toward you, the pitch is higher than when it's moving away. You're hearing a shift in the wavelength of the sound waves reaching your ears. The same thing happens with light, except that the difference is so slight that we don't see it in the world around us. Astronomers have to make extremely detailed measurements to detect blue- or redshifts, but they can then work out the exact speed with which an object is moving toward or away from Earth.

When Hubble (the astronomer, not the telescope) measured the redshifts of galaxies in the 1920s and 1930s, he discovered a pattern: the more distant the galaxy, the greater the redshift. Thus, the farther a galaxy is from us, the faster it's moving away. This observation was the first clue that we live in an expanding universe, but it also means that, in order to study galaxies at great distances, we have to observe them at "high redshifts."

So what does this have to do with infrared? Well, if you look at galaxies far enough away, the light from stars has redshifted considerably, so that the most interesting wavelengths to study are in the infrared. If most stars emit the majority of their light at visible wavelengths, then you can image that a shift toward longer and longer wavelengths eventually means that most of the starlight now appears at infrared wavelengths. Thus, with an infrared telescope, an astronomer can make observations of very distant galaxies whose light is redshifted out of the visible range of the spectrum.

Astronomers have a very compelling reason to observe distant, highly redshifted galaxies: they date from an earlier epoch in the history of the Universe. The light from these distant galaxies has been traveling for billions of years, which means we're seeing these galaxies as they were billions of years ago. You're seeing the opposite side of the room as it was a nanosecond ago, the

Moon as it was a second and a half ago, and the Sun as it was eight minutes ago. When one talks about galaxies, however, the distances become large enough, and the light travel time long enough, that it becomes somewhat mind-boggling. The history of the Universe is spelled out in observations at high redshifts, and studying distant galaxies in infrared wavelengths allows us to learn about how the Universe has evolved over time.

Astronomical Tools

One of the challenges of infrared astronomy is where to do it. Unfortunately for astronomers, Earth's atmosphere contains water vapor and carbon dioxide that absorb most (but not all) of the infrared light coming to us from the rest of the Universe. Only in specific wavelength ranges can light reach a ground-based telescope, which means that other tools are needed to study infrared astronomy (Figure 6). The most important thing is to get above the absorbing water and carbon dioxide, so some infrared astronomy is even done from high-flying airplanes! Quite soon, the Stratospheric Observatory for Infrared Astronomy (SOFIA) telescope will take to the air—a ten-ton telescope on a 747 will fly more than 40,000 feet, above most of Earth's atmosphere. But the best view for infrared astronomy, particularly at very long, cool wavelengths, is attained from space.

The Infrared Astronomical Satellite (IRAS) gave astronomers their first view of the far infrared sky back in the early 1980s, and a few other satellite observatories followed. The Hubble Space Telescope was equipped with an infrared camera on its first servicing mission in 1993. And the Spitzer Space

Telescope, launched in 2003, currently provides an unprecedented view of the infrared sky—with extremely sharp images at a wide range of wavelengths.

Astronomers can still make useful infrared observations from Earth, however. They take advantage of specific wavelengths of light that manage to make it through Earth's atmosphere, making infrared observations from the ground as well as from airplanes and spacecraft. In fact, there are some added benefits to doing so. Space-based missions cost quite a bit to build, and once they've been launched, it can be tricky to make repairs or upgrades. And although a 747 is much more accessible than a satellite, it still proves more challenging than driving up a mountain. Furthermore, infrared astronomy can take advantage of exciting new technological advances in telescope design.

One of the most powerful techniques used in modern telescopes is called adaptive optics. Turbulence in the atmosphere, the same atmospheric effect that causes stars to twinkle, also causes ground-based telescopes to have blurrier images than their space-based counterparts. Adaptive optics rapidly change the optics of a telescope (usually physically altering the shape of one of the mirrors in a large telescope) to correct for atmospheric turbulence. This allows astronomers to compensate for some of the limitations of observing from the ground.

Because infrared light scatters less in the atmosphere than visible light does (remember that longer wavelengths don't scatter as much as shorter wavelengths), adaptive optics techniques work better in infrared than in visible light. The turbulence is easier to compensate for, and the telescope produces a sharper image.

Many so-called "new technology" telescopes use adaptive optics, and as a consequence, most are designed to work well in the near infrared. The Keck, Subaru, and Gemini Telescopes are just a few examples of giant new observatories built to take advantage of observations in the infrared.

The Future of Infrared

The future of infrared astronomy seems to grow brighter all the time. The study promises new discoveries in many areas of interest—from the distant early Universe to the search for life nearby—as well as capitalizing on sophisticated tools and the latest technology. Astronomers hope to use infrared observations to answer some of their most tantalizing questions. What was the Universe like in its earliest history? How did the elements to make life come into existence? How do planets form? Are there planets like Earth orbiting other stars? The answers will be pieced together from many clues after decades of work, but many of those clues will certainly come from observations at infrared wavelengths.

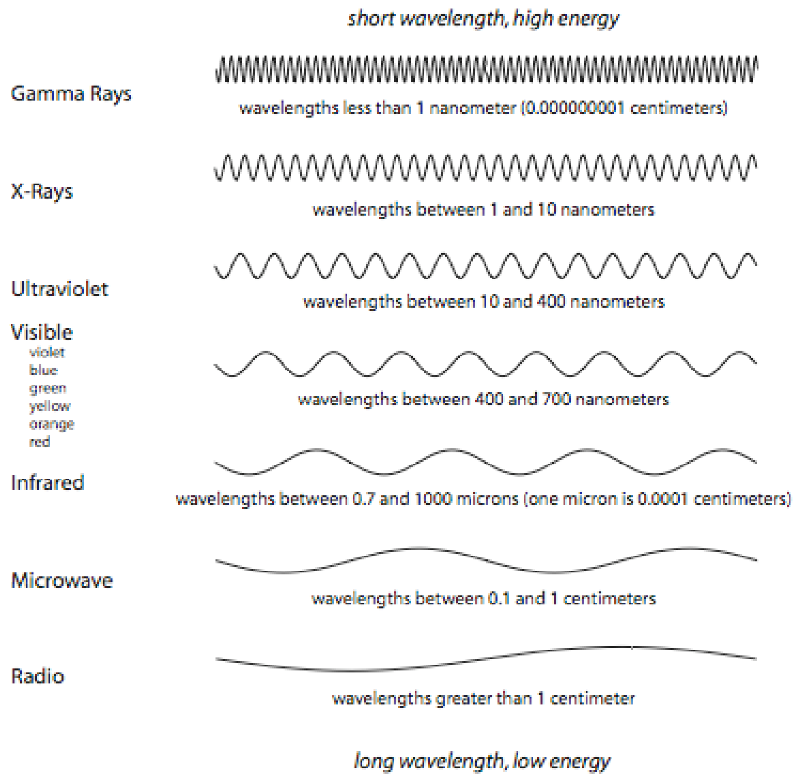

Figure 1. Visible light, the light we see, is only a small part of the entire electromagnetic spectrum. Shorter wavelengths carry more energy than longer wavelengths; gamma rays are the shortest-wavelength, highest-energy form of light, while radio waves are the longest-wavelength, lowest-energy form.

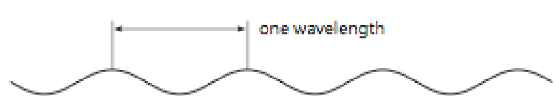

Figure 2. One wavelength is equivalent to the distance between peaks or troughs in the changing electric or magnetic field of a light wave.

Figure 3. The galaxy M81 seen in visible light (left) and infrared (right). Very little starlight is seen in the infrared image; instead, bright clumps highlight regions of warm gas and dust where stars are forming.

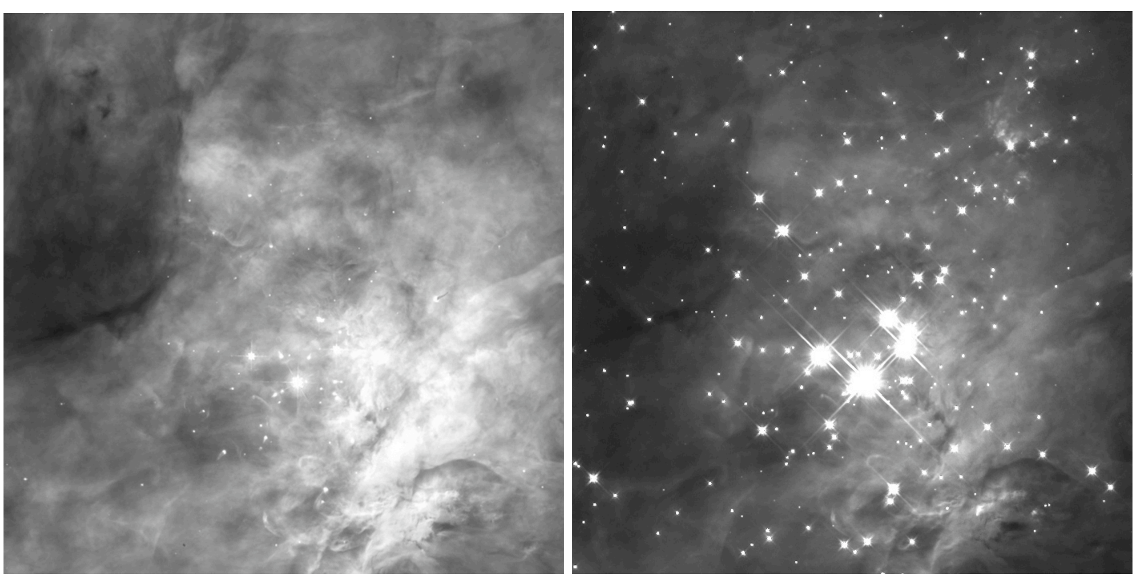

Figure 4. The Orion Nebula seen in visible light (left) and infrared (right). The infrared image shows numerous young stars, still shrouded in the gas and dust from which they formed—gas and dust that obscures the stars in visible light.

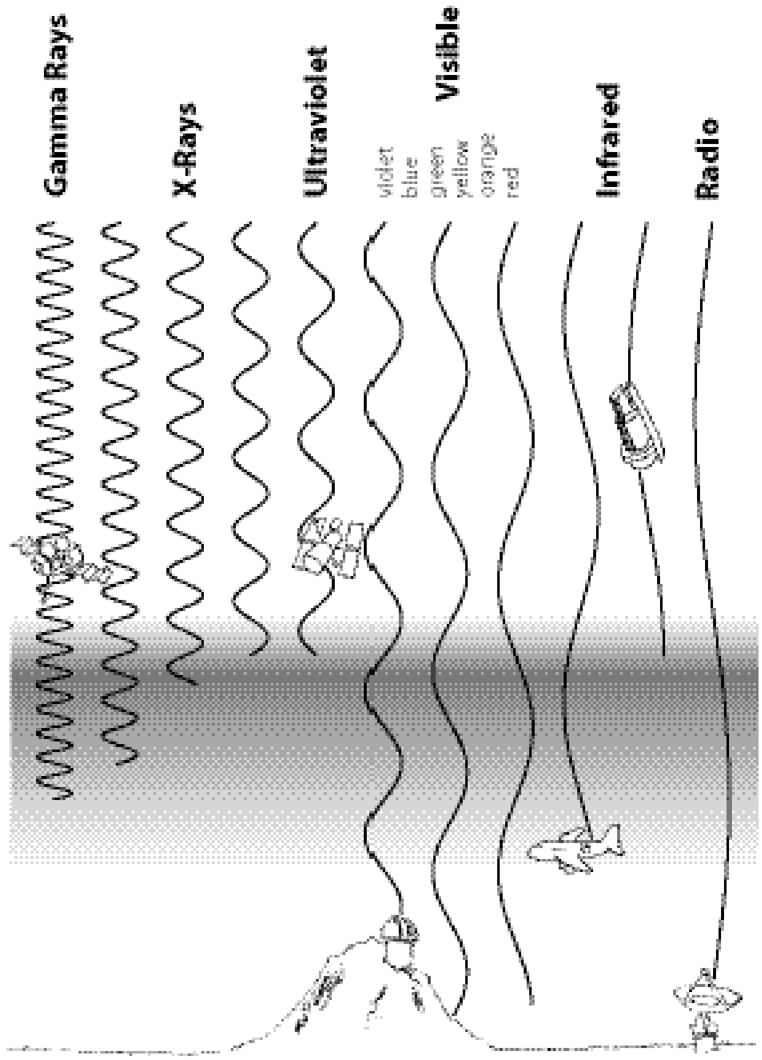

Figure 5. Earth's atmosphere blocks many wavelengths of light. In order to observe certain wavelengths, astronomers need to build airborne telescopes or satellite observatories to get above the deleterious effects of the atmosphere.

Note: Images in Figure 4 courtesy of NOAO/AURA/NSF and NASA/JPL/SSC. Images in Figure 5 courtesy of NASA/STScI.

About the Author

Ryan Wyatt is a science visualizer at the Rose Center for Earth & Space, American Museum of Natural History, in New York City. He also teaches numerous courses for the Hayden Planetarium, on topics as diverse as 20th-century astrophysics and the history of science. Ryan has worked in planetariums and astronomy education for the past thirteen years, opening world-class planetariums in Phoenix, Arizona, and Albuquerque, New Mexico. He received his undergraduate degree in astronomy from Cornell University in Ithaca, New York, and completed graduate work in space physics and astronomy at Rice University in Houston, Texas.