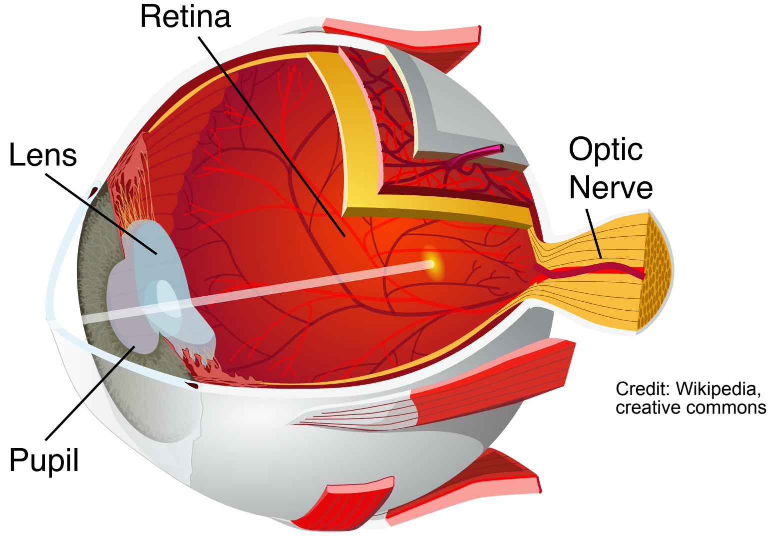
Yeah we all shine on,
like the moon, and the stars, and the sun.
John Lennon

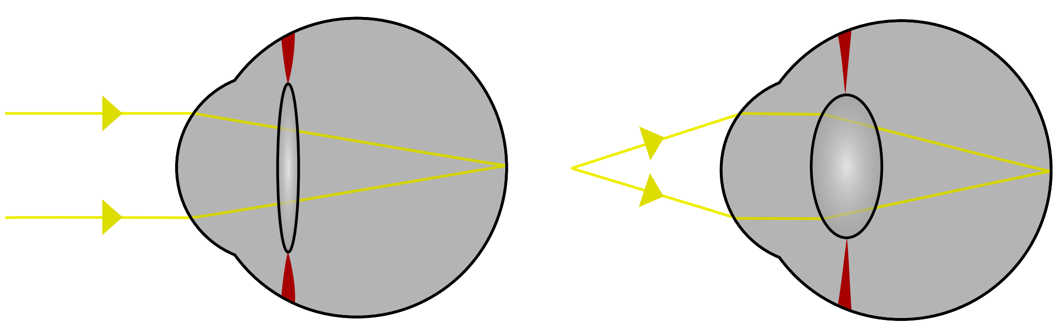
How We See

Hi AST 111/113. In this module we'll explore how astronomy has and does record the photons that come out of the barrel of a telescope.

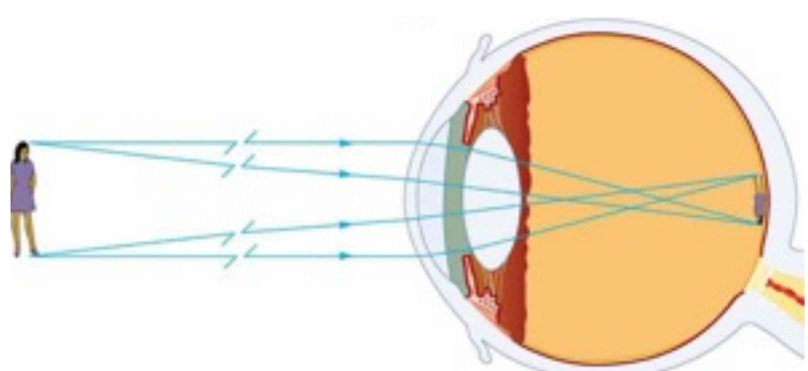


Credit: Wikipedia, creative commons

The human eye was the first astronomical detector. Your eye lens brings light to a focus on your retina. While being a relatively crude lens, your eye is attached to the most fantastic image processing system on the planet - your brain - which corrects for all kinds of stuff.



Credit: Wikipedia, creative commons



Credit:OpenStax, creative commons

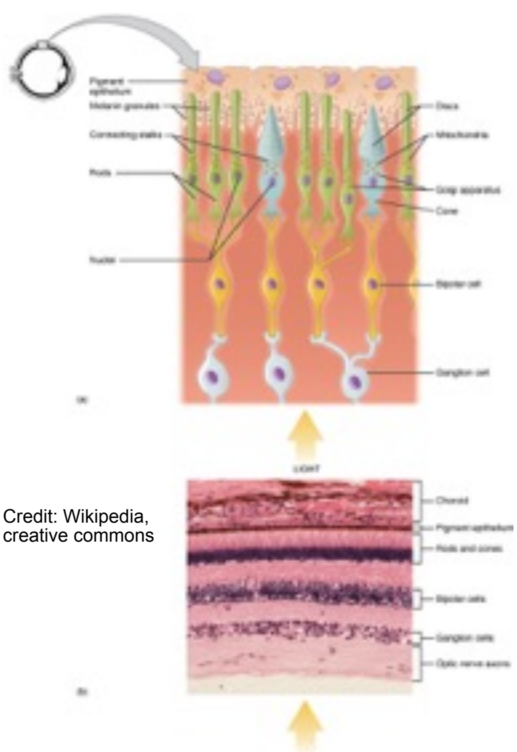
For example, your eye lens is adaptive, flexible. As shown in the first image above for more distant objects the light rays are coming in nearly parallel and your lens stretches into a thinner more elongated configuration. For more nearby images, the eye's lens takes on a squatter more compact configuration. The image processing system between your ears takes care of that. In addition, like any lens, the image that forms on the retina is upside-down. As shown in the second image above. Again, your image processing system comes to the rescue by inverting the upside-down image to right size the world for you. And of course with two eyes, two angles of view, the brain does a parallax calculation to give us depth perception, to give us the third dimension of our world.

This said, as an astronomical detector, the eye has several deficiencies. For every 1,000 photons that goes into your eyeball, only about one of them is captured. In other words, 99.9% of the light that goes into your eye is wasted. That's not good for astronomy because you work so hard and spend so much money to gather and control the captured light. You don't want any of it wasted.

Our eyes also see in the optical only. It's good for us, because that's where the maximum of the Sun's output is. But we don't see in the infrared. We don't see in the ultraviolet. We don't see in any of the other electromagnetic bands. That's bad for astronomy because other wavelengths often say much more about an object.

Our eyes also have a logarithmic sensitivity, which allows you see in very dim light and in very bright light as your pupil opens and closes in order to adjust to the amount of light. But it's not good for astronomy, where we want a linear detector, so that if I double the number of photons going in, I double the signal going out. That's not what happens with your eye: you double the number of photons going in your eye, and you only see about a factor of 1.3 times brighter.

And, of course, your eye is no permanent recording device. You have to sketch what you see, which is what early astronomers did. Or you have to remember what you saw. Gasp.

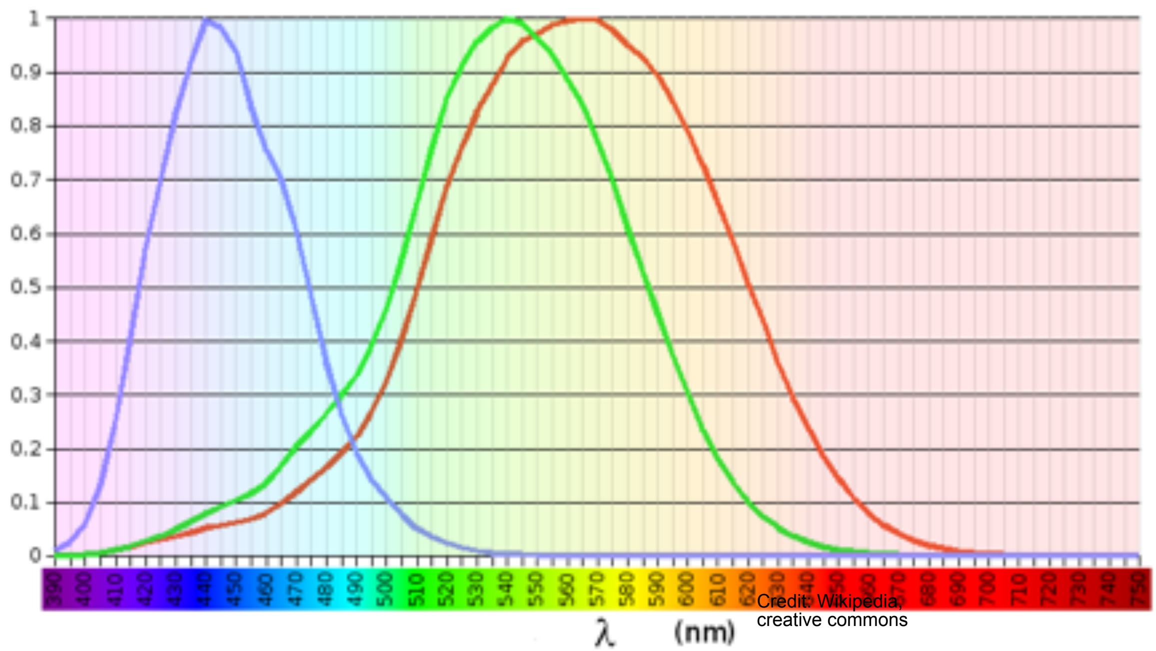


Credit: Wikipedia, creative commons

As a small aside. On our retina, what actually catches that 0.1% of the light coming are about 120 million rods and 10 million cones. Rods are sensitive to motion and dim light. Cones are sensitive to color. You can probably guess why from an evolutionary survival perspective it's advantageous to have many more rods than cones.

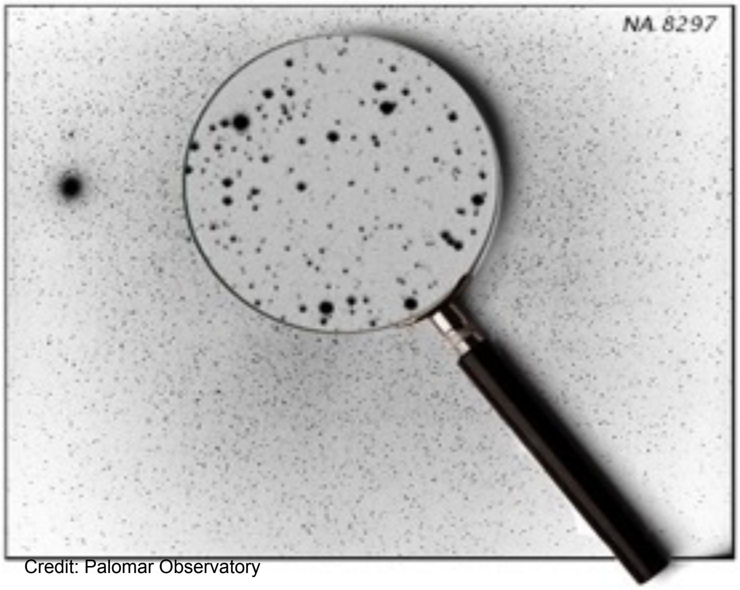
Your eye is also not an integrating device. Stare at an object for as long as you want, but the object doesn't get brighter. It stays the same brightness. That’s because our eye's integration time is about 1/20 of a second. After 1/20 of a second it refreshes. This is why movies run at 24 to 30 frames per second, slightly faster than the eye's integration time. Although you know a movie is a just series of still images, its run at a speed a little bit faster than what your eye can integrate. Therefore, motion comes across as a smooth. What astronomy wants though is an integrating device - the longer one looks the brighter is gets as it adds up the photons coming it.

Finally, the rods and cones in our eyes have large pixel sizes, if you'd like to express it in the terms of the digital age. They're about a tenth of a millimeter or so, which is quite a bit larger compared to digital camera pixels. The images below show the response curve of the cones in the back of our eye to different wavelengths (colors) of visible light.

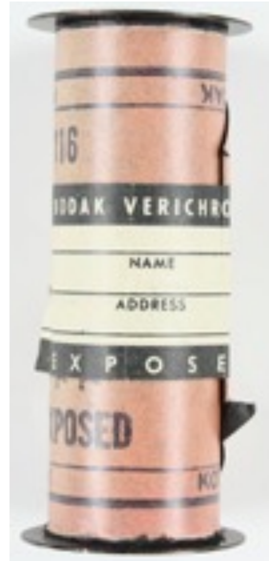


Credit: Wikipedia, creative commons

Another small aside. Of those 10 million cones, about 65% are devoted to red, 33% to green, and 2% to blue. Our brain takes care of mixing to get all the other colors. Although we don't have many blue rods, they are the most sensitive, which is what the plot to the right shows.



Credit: Palomar Observatory

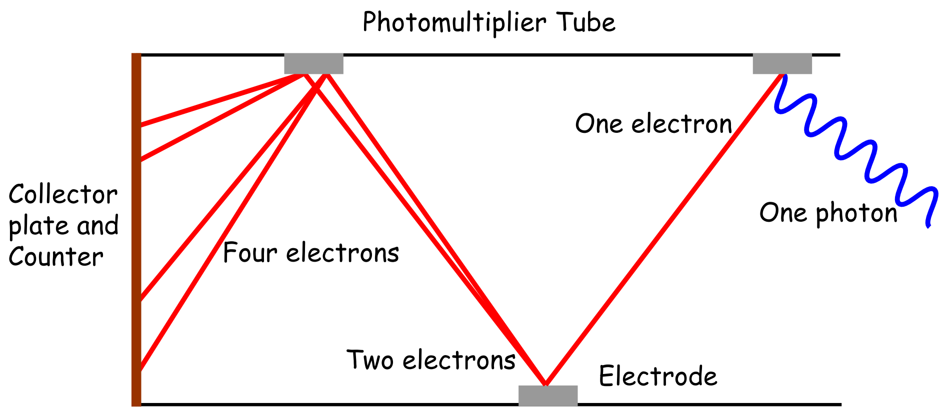


Credit:Victoria Museum, creative commons

Astronomy's second detector was photographic, first glass plates (left image above) and then plastic film (right image above). This technological revolution came in about 1840 or so. With photographic film, 1 in every 50 photons is detected. Better but still wastes 98% of the light. Film, of course, has the advantage of giving a permanent record. It is an integrating device. You can overexpose film. If you open the shutter long enough, the image will be all black.

The pixel sizes in photographic film are fantastic. They're on the order of the size of molecules, silver nitride, about 10^{-7} meters. If you're looking for maximal resolution, film is king. Although, as technology marches on, the pixel sizes of digital devices is getting smaller and starting to approach what film can do.

Film, unfortunately, is still a non-linear sensitivity. It's not as bad as your logarithmic eyeball. But it's still not linear. Film is also better in that you can capture infrared and ultraviolet wavelengths in addition to visual light wavelengths.



Credit: F.X. Timmes


Credit: Wikipedia,
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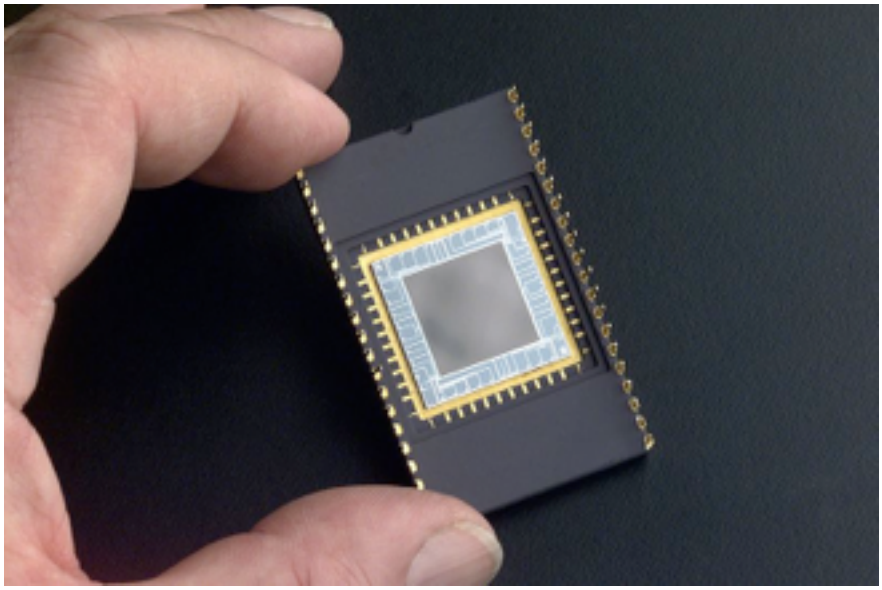
Astronomy's third detector was the photomultiplier tube, which came in circa the 1940’s. It's a better detector in that for every five photons that goes in, one of them is captured. So only now about 80% of the light is wasted.

How a photomultiplier works is shown in the image above. A photon comes in with a certain amount of energy and hits an metal electrode. If there's enough energy in that photon, it will knock an electron off that electrode. There's also a potential difference, a voltage across the device.

The freed electron now accelerates and hit another electrode. Since you've accelerated it with the voltage difference across the electrode, the electron has more energy, and it can knock two electrons off that second metal electrode. And so on. You can multiply the number of electrons arbitrarily two, four, eight, 16, whatever it happens to be. Ultimately, these freed electrons hit your collector plate where you count how many electrons you get. Finally astronomy has a linear detector. If you double the number of photons that go into the tube, you double the number of electrons coming out. Hurray!

A photomultiplier gives a permanent record, and it's an integrating device. Like film, you can over expose it.

A disadvantage of a photomultiplier tube is that it's a point detector. You're essentially taking a very thin tube and getting one pixel. So if you want to make an image of something, you have to sweep the photomultiplier tube across the object. You have to move the photomultiplier tube in order to build up an image. And that takes some time.



Credit: Wikipedia, creative commons

Astronomy's fourth detector came in the 1980s. That's the Charge-Coupled Device, or CCD. Each pixel in a charge-coupled device acts like a miniature photo multiplier tube. The principle of operation is similar; a photon goes into one of the cells of the CCD. It multiplies the number of electrons that are coming off the silicon. Those electrons are collected and then counted.

CCDs are fantastically efficient devices. They only waste about 10 percent of the light going in. So for every 1.1 photons coming in, you capture one photon. They are also linear detectors; doubling the light doubles the electrons collected.

They are, of course, digital. So that comes with a price tag: now you have to have some fancy electronics to create and read those images. And the pixels still aren't quite as small as those of photographic film, but as we mentioned above, they are starting to approach the high resolution of film.

What will astronomy's next detector be?!

Shine on! Bye Bye.