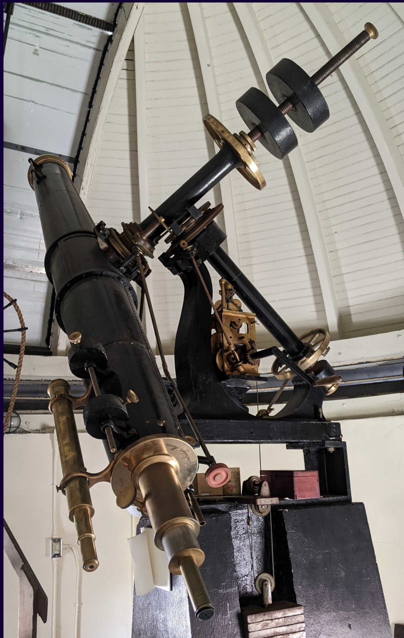
From Holden to Webb: The History and Future of Telescopes

Syracuse University Physics
Walter Freeman

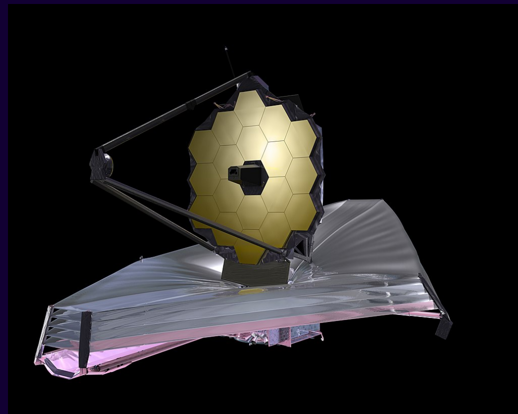
November 2, 2022

How did we get from here ...

... all the way to here?



Telescope in Holden Observatory, Syracuse University (1887)



Illustration, James Webb Space Telescope
(NASA / ESA / CSA)

Outline

- The Holden telescope: What is a telescope, anyway?

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2. In pursuit of size: why is bigger better?

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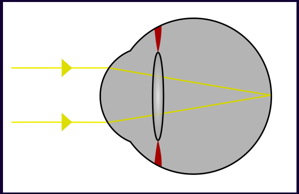
2. In pursuit of size: why is bigger better?
3. Problems from the atmosphere
4. Somewhere over the rainbow: the spectroscopic revolution
5. To space: the Hubble Space Telescope
6. The Webb telescope: solving problems in infrared astronomy
7. JWST scientific goals and images

What is a telescope?

A telescope is just a really big eyeball!

Use a big lens or mirror to gather light and focus it to form an image.

It's just like an eyeball...



... or a camera lens:

- Using a shorter focal length lens produces a less magnified image
- Using a longer focal length lens produces a more magnified image

Eyepieces

These images can be too small to see well with the eye!

This makes sense if you compare a telescope to an eyeball:

- The image focused on an eyeball's retina is easy to see if you're the owner of the eyeball

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- If you're an optometrist, you need a magnifying glass to see the image focused on someone else's retina

These "magnifying lenses" for telescopes are called *eyepieces*.

Early astronomers needed them since we can't put our retinas where the telescope makes its image...

... but now we don't need them.

The resolution limit

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Seeing faint things

Telescopes let us see faint things.

The larger the aperture, the more light it gathers.

If you want to see things in dim light (or faint stars), you need big eyeballs!

The amount of light gathered is proportional to the square of the aperture diameter, since

$$A = \pi r^2.$$

Seeing small things

Surprise: a larger aperture also lets you see *smaller* things.

- Light spreads out as it goes through a hole or past an edge
- This is called diffraction
- The larger the hole, the less diffraction you get

Examples of diffraction from Bob Atkins from a camera. Left: 75 mm aperture. Right: 9 mm aperture

Seeing small things

From physics, assuming perfect optics:

$$\text{smallest detail visible} = 2.5 \times \frac{\text{wavelength of light}}{\text{diameter of telescope}} \times \text{distance to object}$$

Example for one of Galileo's telescopes, considering Jupiter:

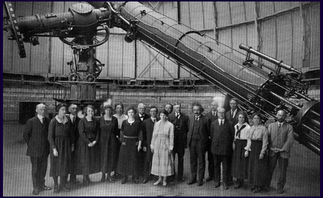
$$\text{smallest detail visible} = 2.5 \times \frac{600\ \text{nm}}{26\ \text{mm}} \times 750\ \text{million km} \approx 50,000\,\text{km}$$

(Io is 500,000 km from Jupiter, so this would be visible!)

The pursuit of bigger apertures

Telescopes made with lenses (like our eyeballs) have some problems:

- They have to be very long (or sacrifice optical quality)
- Large-diameter lenses get thick, expensive, and heavy



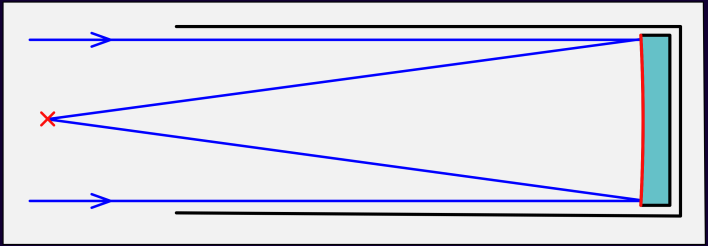
40" refracting telescope at Yerkes Observatory, 1921

- They still suffer from *chromatic aberration*
  - Lenses don't focus all colors of light the same
  - This gets worse with increasing aperture
  - It can be partially corrected but the lenses get even bigger

Stan Zurek / Wikimedia Commons

Solution: use mirrors

A mirror requires only a thin surface of optical material, avoids chromatic aberration, and is far easier to make.



Oleg Alexandrov / Wikimedia Commons

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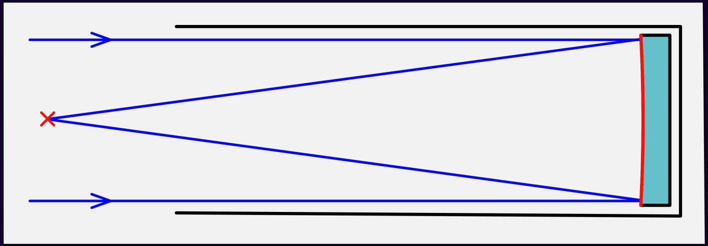
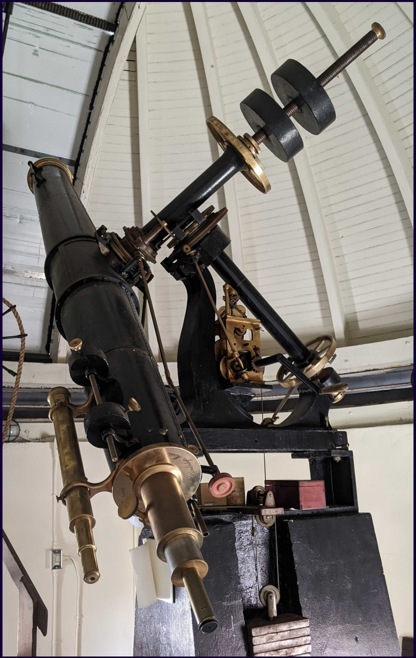


Oleg Alexandrov / Wikimedia Commons

The telescope I have here is bigger than the Holden one!



Stop twinkling, little star!

Stars twinkle because of random refraction from Earth's atmosphere.

This is pretty, but it makes astronomers grumpy.

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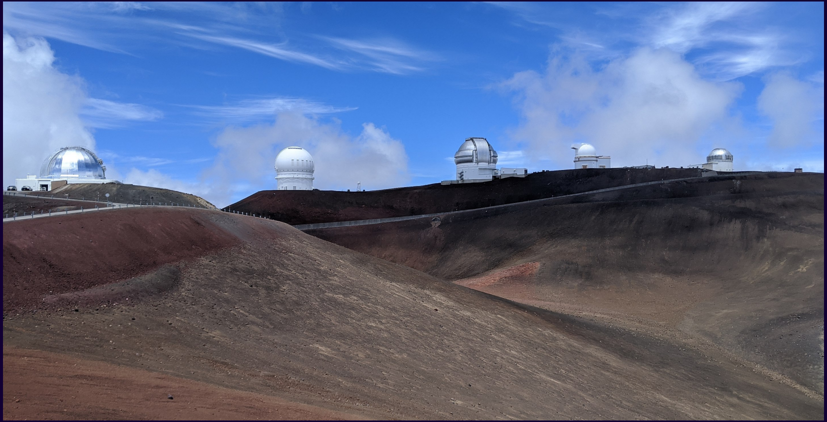
This is pretty, but it makes astronomers grumpy.

Solution: look for dry, thin, stable air on the tops of mountains!



Telescopes in Mauna Kea, Hawai'i (13,800' elevation) - Leijurv / Wikimedia Commons

Improving on the Holden scope, so far

Now we know how to:

- Achieve bigger apertures with smaller telescopes using mirrors
- Dispense with eyepieces by using film (or digital sensors) at the focal plane
- Build telescopes in places with less twinkly skies

... what's next?

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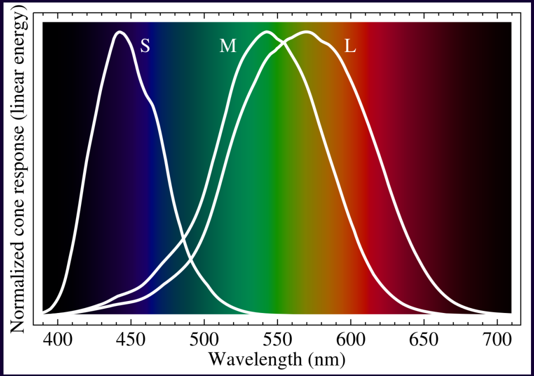
Next step: improve the color "vision" of telescopes beyond the human eye!

Seeing more precise color

Even within the visible range, our eyes are extremely limited:

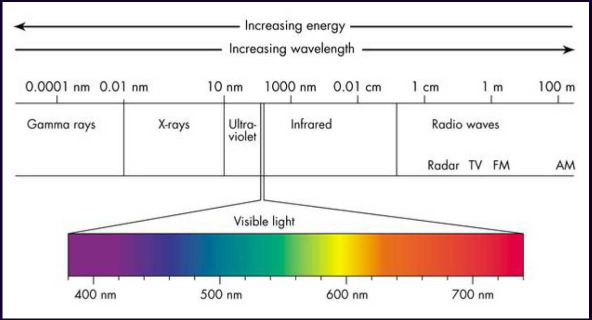


The human eye can only see three different colors. Other shades like orange are a mixture of these.

Solution: separate out the wavelengths of light using a prism (then) or diffraction grating (now)

Seeing a wider range of colors

There is a vastly wider range of light than we can see.



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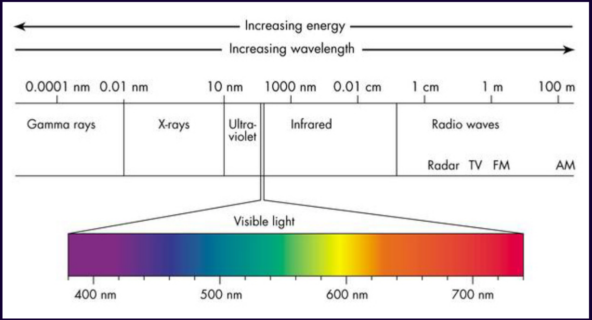
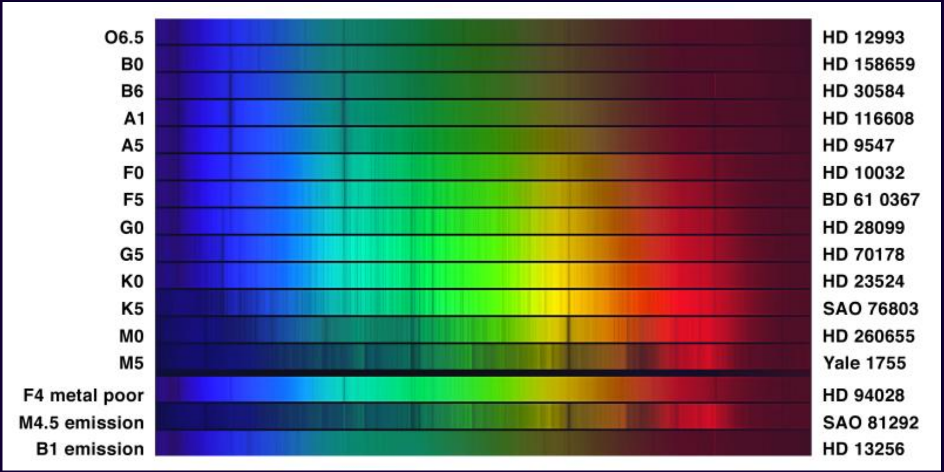


That's okay – we already know eyes aren't great companions to telescopes.

- Photodetectors (even film) can see a much wider range of colors
- Colors near the visible range reflect from mirrors too!

The spectroscopic revolution

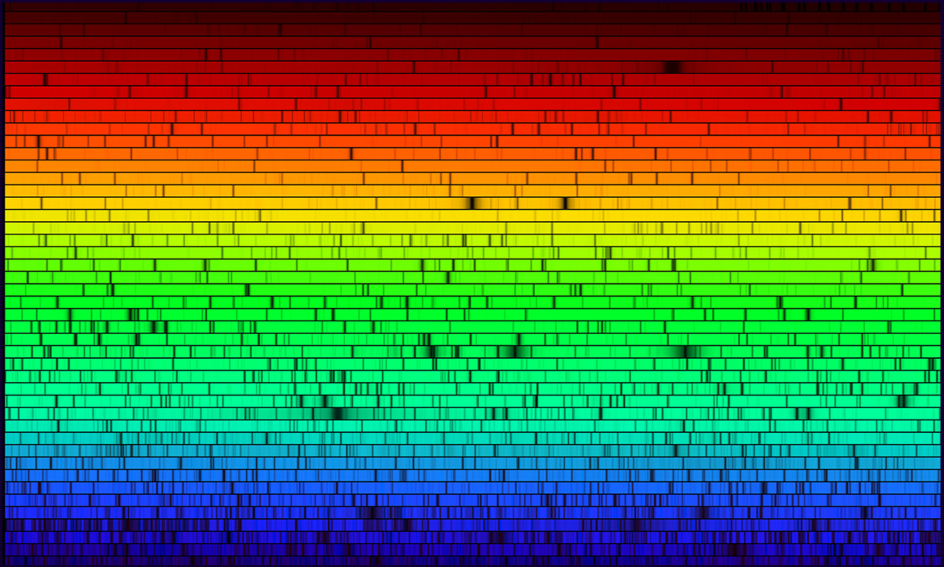
There's a wealth of information about stars we can get from their spectra.



All stars mostly have the same spectral lines, but their prominence tells us things like stars' temperatures and compositions.

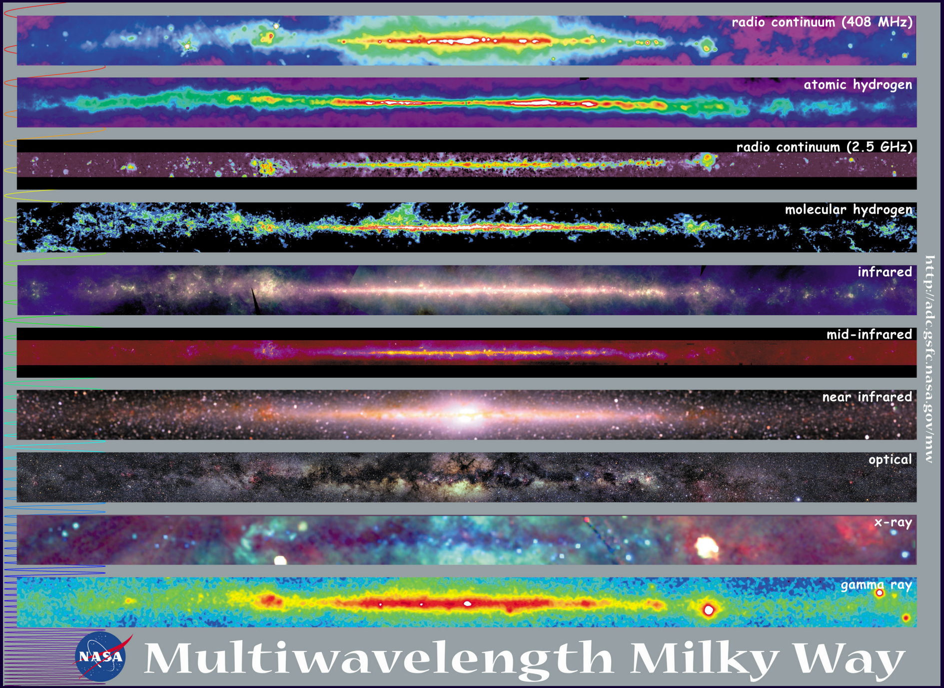
The spectroscopic revolution

"There are holes in the rainbow and they tell us we are made of stardust".

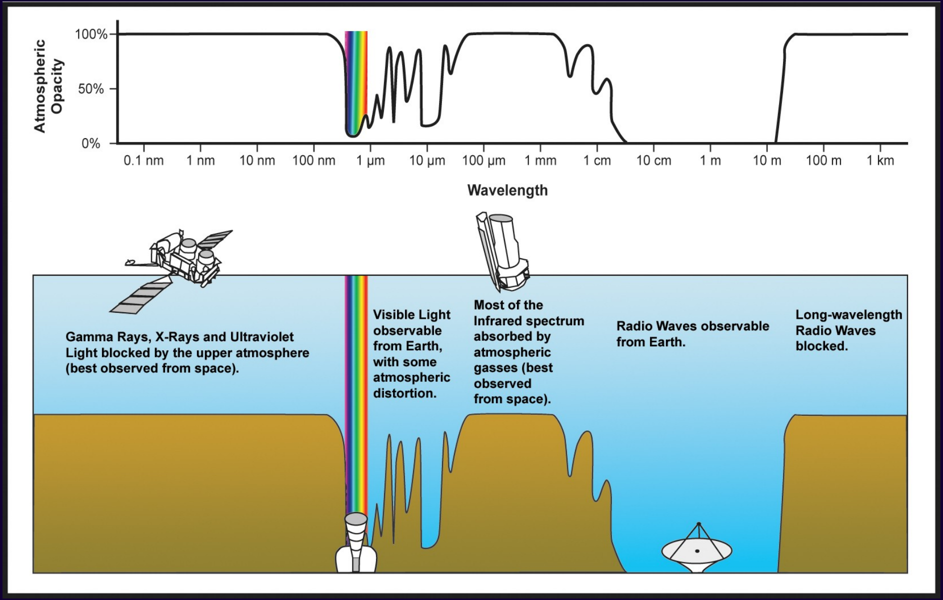


(NASA / public domain)

The need for all wavelength bands



The atmosphere is a problem (again)



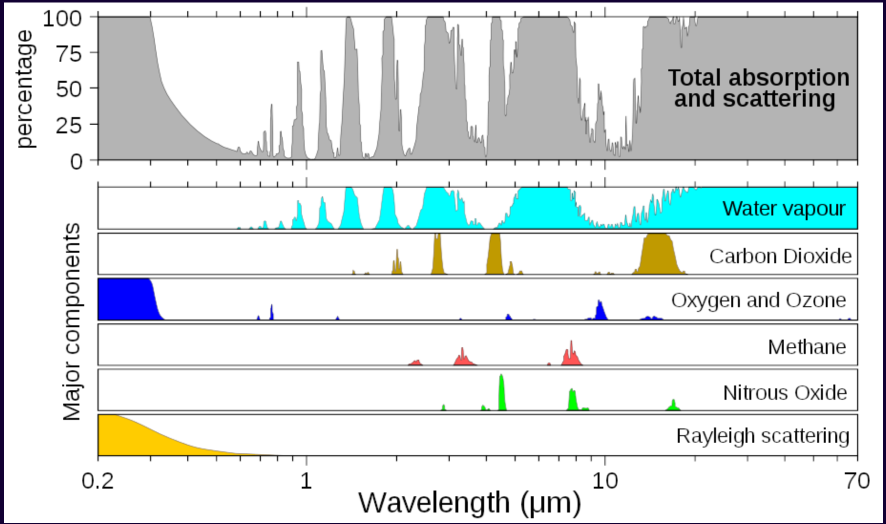
(NASA / public domain)

Astronomy in the infrared and ultraviolet is very hard to do from Earth!

Why the infrared matters, I

Planetary scientists are interested in atmospheres.

We can't see the signatures of chemicals in other planets' atmospheres if ours is in the way!

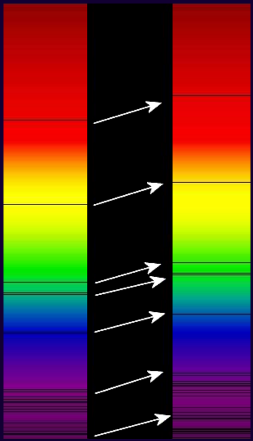


Wikimedia Commons / Global Warming Art Project

Why the infrared matters, II: the redshift

The Doppler effect means that light from things moving away from us is shifted to longer wavelengths.

Since red light has longer wavelengths than blue light, this is called the "redshift".



Georg Wiora / Wikimedia Commons

We can figure out relative motion of stars from their Doppler shift.

Surprise:

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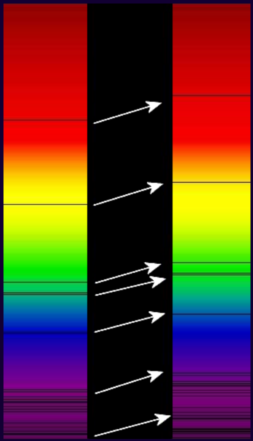

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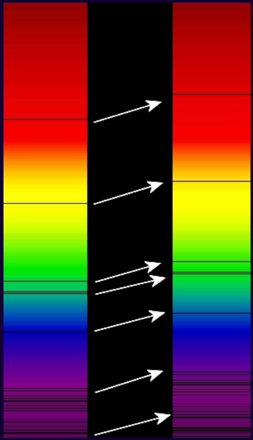

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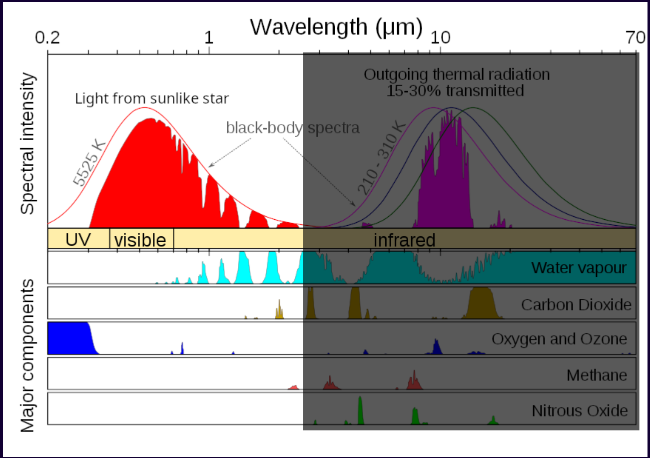
- Most everything is moving away from us
- The more distant they are the faster they're moving away
- The oldest and furthest things in the Universe are redshifted by a *huge* factor:
  - Oldest galaxies: 15x wavelength
  - Oldest stars: 20-30x wavelength

Telescopes in space: Hubble

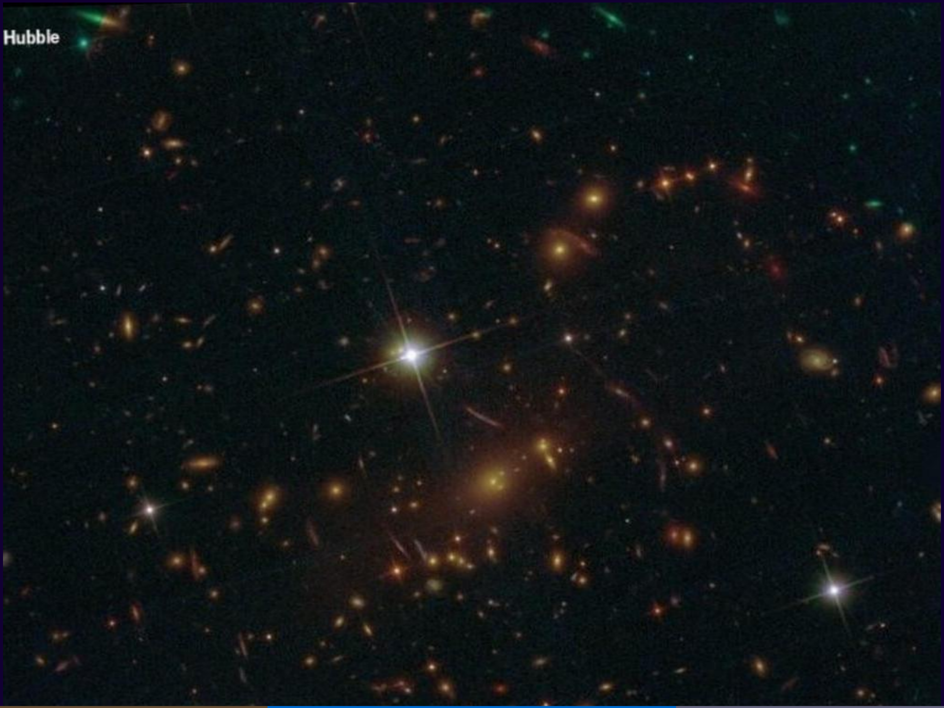
Putting a telescope in space lets us see into the infrared!
(and avoid the other problems the atmosphere causes too)

Putting a telescope in space lets us see into the infrared!
(and avoid the other problems the atmosphere causes too)

- Visible + near-infrared telescope in low earth orbit
- Sensitive from 90 - 2400 nm (ultraviolet to near infrared)



Hubble was the new hot thing!



The problem with the hot new thing

Everything with a temperature produces light.
This is called *thermal radiation* or *blackbody radiation*.

Hotter objects produce shorter wavelengths:

- Stars like the Sun: thousands of Kelvin, wavelengths around 500 nm (visible)
- Hotter stars: tens of thousands of Kelvin, mostly ultraviolet

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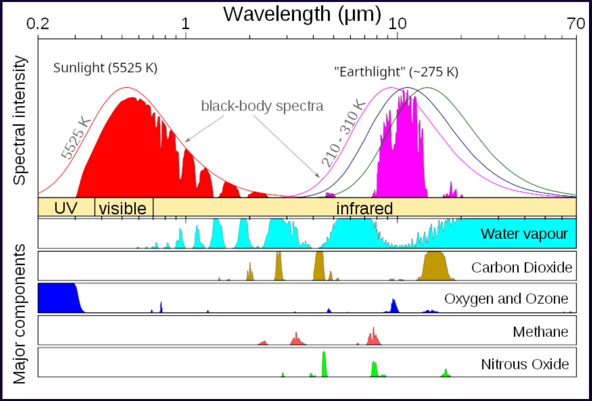

Cooler objects produce longer wavelengths:

- Earth-temperature things: hundreds of Kelvin, wavelengths around 10,000 nm
- This is the famous "heat vision" – it's not heat, it's just long-wavelength light

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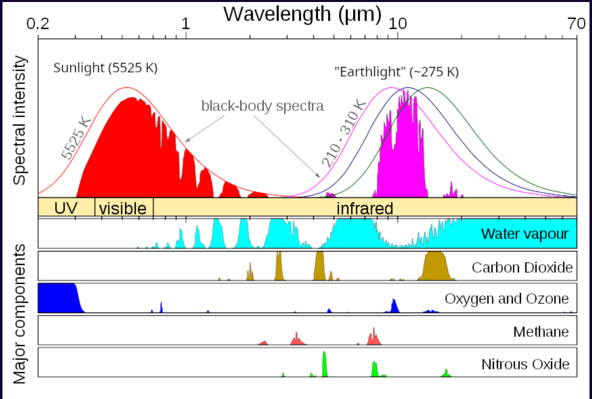

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Hubble is blinded by its own thermal radiation when trying to see the early universe!

The Webb Space Telescope

Goal: Make highly detail observations from the visible to the infrared.

- Put it in space (no pesky air)
- Make it big
  - Earth-based telescopes now use honeycomb mirrors for easier manufacturing
  - NASA had to figure out how to fold one up
  - ... and unfold it in space without breaking it
- Keep it in the shade so it's cool
  - The Earth and Moon produce infrared, so we have to shade it from them as well
  - It's parked in an orbit so that the Earth, Moon, and Sun are always on the same side

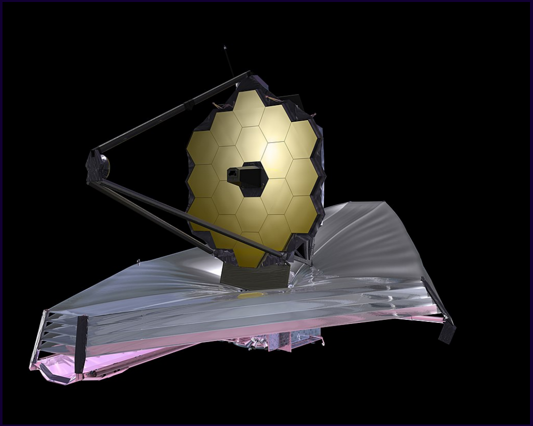
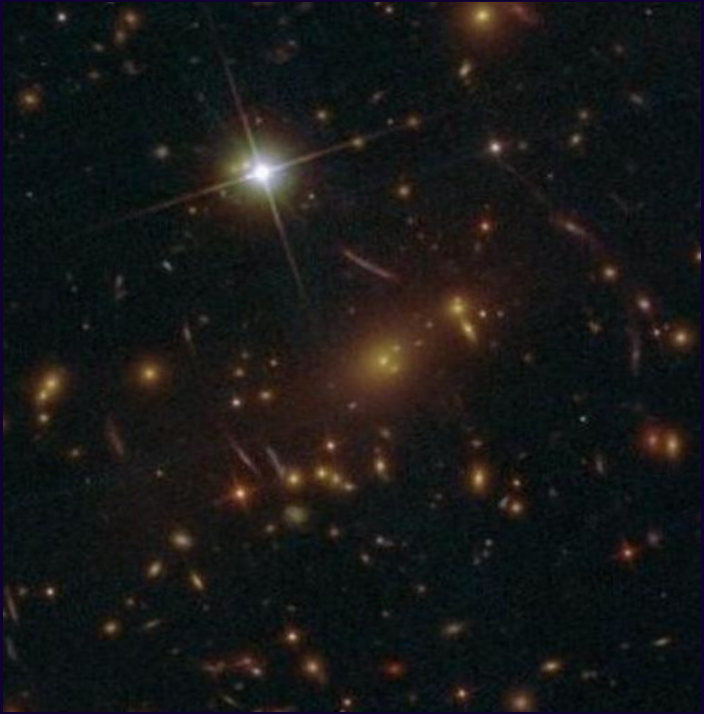


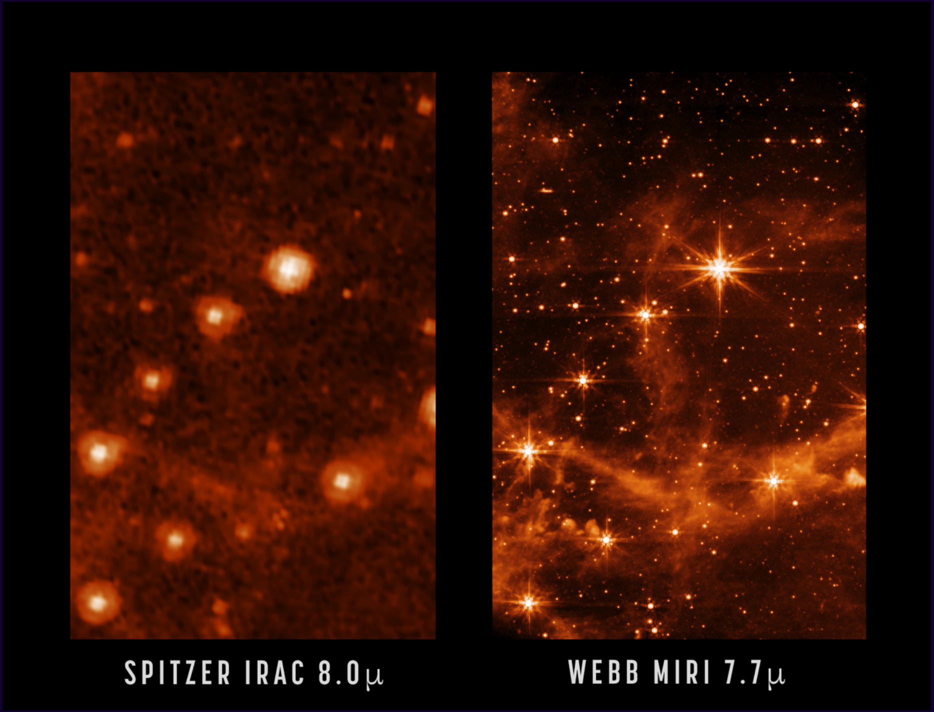
Illustration of JWST. We didn't unfold it on the ground and it doesn't have a selfie camera. :(


Hubble Space Telescope deep field (NASA)

JWST deep field (near-infrared, similar to visible light)

JWST deep field: far infrared on left, near infrared on right

JWST deep field: far infrared on left, near infrared on right



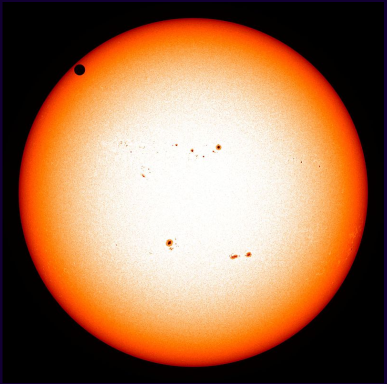
Comparison between JWST and Spitzer Space Telescope

The “cosmic cliffs” in Carina Nebula, an active star-forming region
(near-infrared image by JWST)

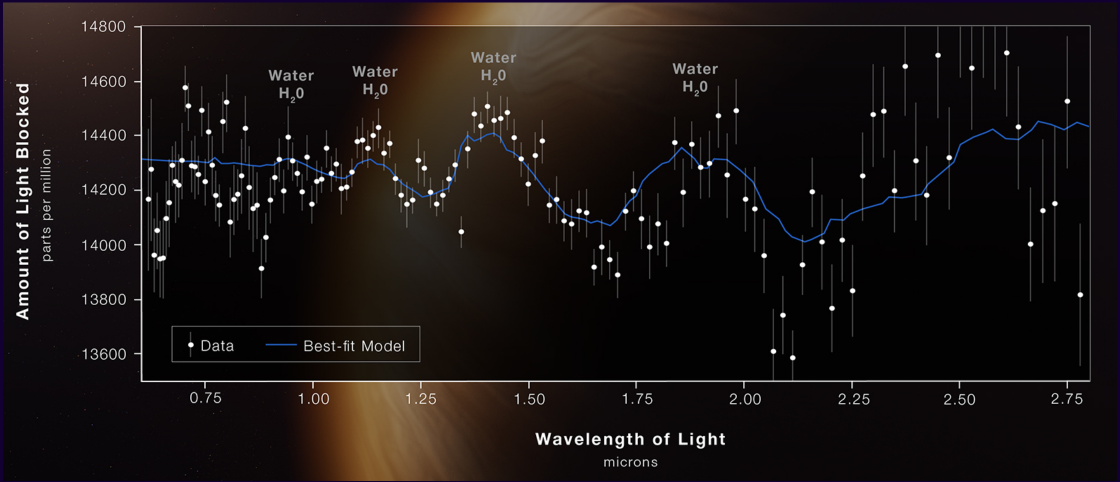
Planetary science with JWST, too

Water absorbs known wavelength bands in the infrared. We've seen its signature elsewhere in our Solar System. What about in planets around other stars? This is really hard. Can JWST do it?

- Image a nearby star known to have a planet
- Wait for a planet to pass in front of it
- All wavelengths will be blocked equally by the planet
- ... but the atmosphere will absorb *extra*

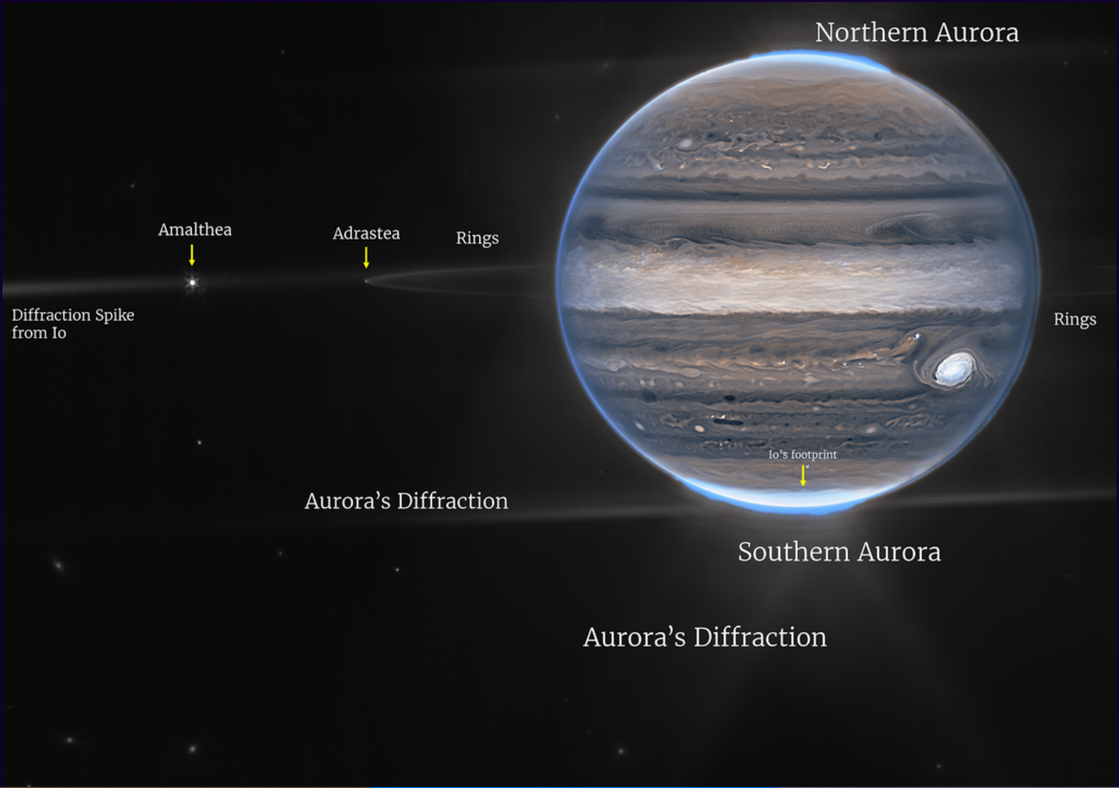


Transit of Venus past the Sun, imaged by NASA's Solar Dynamics Observatory in 2012



Data and presentation from NASA

JWST has seen the signature of water in another solar system!


Northern Aurora
Amalthea
Adrastea
Rings
Diffraction Spike from Io
Rings
Io's footprint
Aurora's Diffraction
Southern Aurora
Aurora's Diffraction

Thanks for coming – please ask questions!

Testing of JWST mirror segments at ultracold temperatures at Marshall Space Flight Center, in Huntsville, Alabama, my hometown. (Image from NASA.)