8 Seeing the Heavens: Telescopes and Detectors

Assign: Read Chapter 6 of Carrol and Ostlie (2006)

We now survey some of the instrumentation that allows us to study objects in the sky.

8.1 Optical Telescopes

Telescopes are devices to gather and intensify light from distant and faint objects. The traditional telescope uses either lenses or mirrors to accomplish this with visible light.

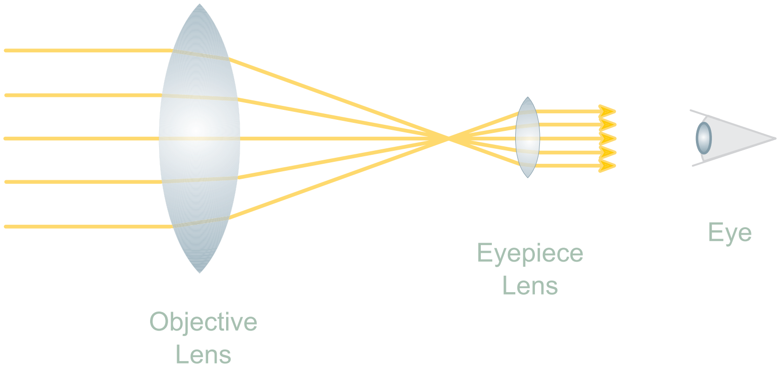
8.1.1 Limitations of the human eye

The human eye was the first instrument used to study the heavens, but it has some limitations:

- The eye has limited size and limited light-gathering power.
- The eye has limited frequency response, since it can only see electromagnetic radiation in the visible wavelengths.
- The eye distinguishes a new image multiple times a second, so it cannot be used to accumulate light over a long period in order to intensify a faint image.
- The eye cannot store an image for future reference (like, say a photographic plate or an electronic detector).

8.1.2 Refracting telescopes

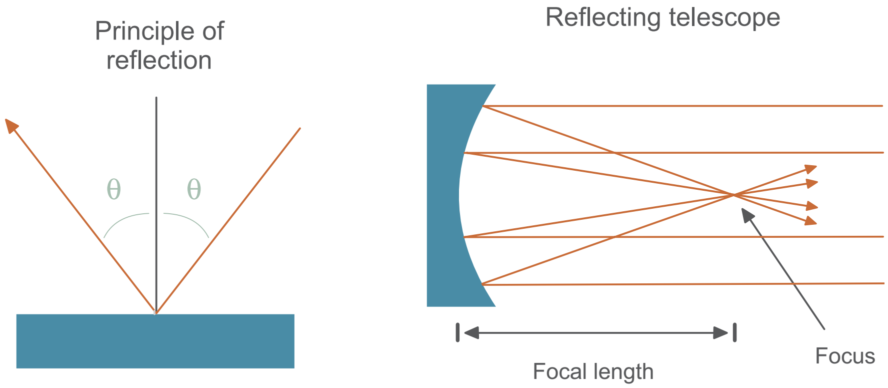
The principle of the refracting telescope is illustrated in the following figure.



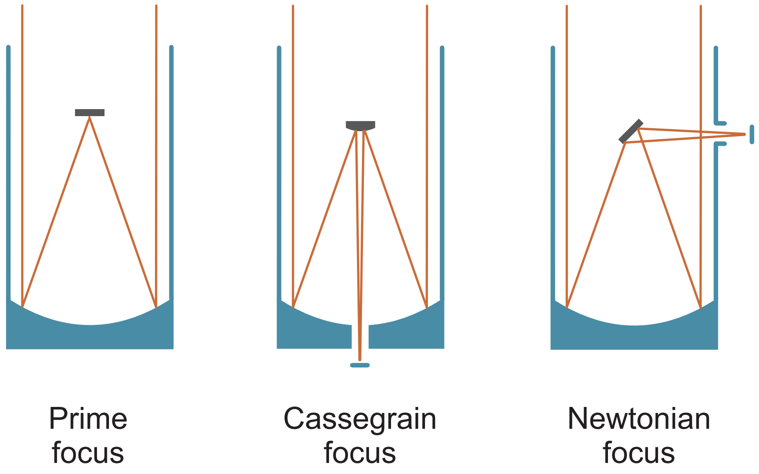
The direction of light is changed four times (twice for each lens) as the light passes between media of different density, with the direction of the change in each case given by the refraction rule discussed earlier. These refractions collect the light and bring it to focus at the observer.

8.1.3 Reflecting telescopes

We may also use reflection from mirrors to design a telescope. The following figure illustrates the principle of reflection: the angle of incidence (measured from the perpendicular to the reflecting surface) is equal to the angle of reflection. The right side of the figure illustrates the use of a mirror to make a reflecting telescope.



Some examples of different ways to get a reflecting focus are illustrated in the following diagram.



> The largest optical telescopes are reflecting, rather than refracting, telescopes. It is easier to build and support large mirrors of high optical quality than large lenses.

8.1.4 Seeing conditions

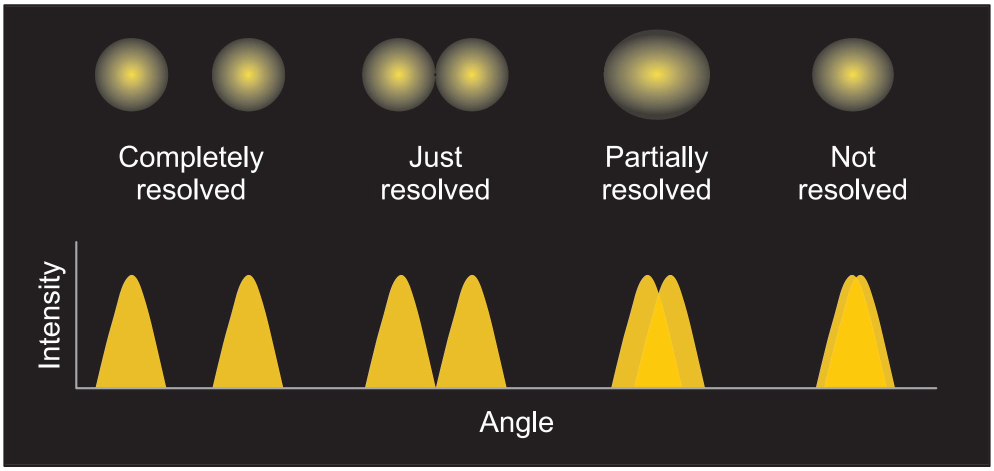
Astronomers refer to the conditions influencing how well objects can be seen with telescopes as the ”seeing conditions.” Several important factors govern the quality of seeing:

1. Even clear air filters out some wavelengths of light very strongly (atmospheric windows).
2. Light from cities and other large light sources drowns out the light of faint objects.
3. The atmosphere contains clouds and dust that block and attenuate light at visible and other wavelengths.
4. The atmosphere is unstable because of vertical air currents produced by solar heating. This “twinkling” effect distorts images.

The best sites for observatories combine stable horizontal air flow, clear skies, high altitude, and remoteness from sources of light pollution. The best sites currently available are the top of Mauna Kea in Hawaii, mountains in the Canary Islands, and certain high peaks in the Andes Mountains of Chile.

8.1.5 Resolution and resolving power

Resolution refers to the ability to distinguish two adjacent objects. The following figure illustrates the idea of angular resolution on the celestial sphere.



Resolving Power

The ability of an optical instrument to resolve two separate objects is called its *resolving power.* Under ideal conditions, the smallest angle α in seconds of arc that can be resolved by a lens or mirror of diameter d for light of wavelength λ is limited by diffraction effects to (*Rayleigh criterion*)

$$\alpha = 2.516 \times 10^5 \left(\frac{\lambda}{d}\right) \text{ arc seconds} \tag{41}$$

where d and λ are measured in the same units.

This illustrates two important properties of the minimum angle that a telescope can resolve:

- It is inversely proportional to the diameter of the lens or mirror.
- It is proportional to the wavelength of light.

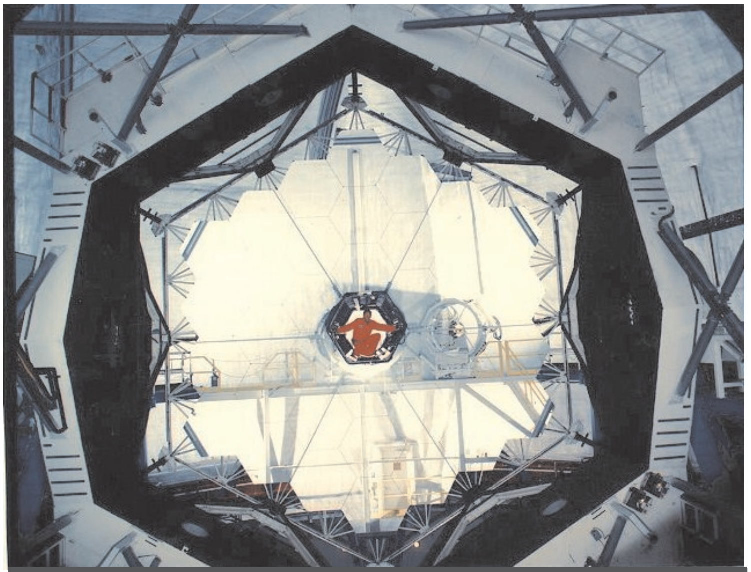
Therefore, resolution improves for a larger telescope, but the longer the wavelength of light the poorer the resolution for a telescope of given size.

8.1.6 Adaptive optics

Modern large telescopes use newer technologies that either combine multiple mirrors or use very thin large mirrors. Then one uses the fast response of a computer to control the elements of a telescope and compensate for changes in the telescope or in the atmosphere that distort the light coming to the telescope.

Adaptive Optics in the Twin Kecks

The twin 10-meter Keck telescopes at Mauna Kea in Hawaii are each composed of thirty-six hexagonal mirrors that are 1.8 meters in diameter. These 36 mirrors combine to form an effective 10-meter mirror, but with each of the thirty-six elements constantly being adjusted by computer to optimize the telescope. In the Keck telescopes, the position of each segment relative to its neighbors is adjusted twice a second, with a precision of 1/1000 the width of a human hair (four nanometers).



Primary mirror of one of the 10-meter Keck Telescopes

8.2 Instrumentation

In modern astronomy the instrumentation that enables taking and analyzing observational data is of central importance.

8.2.1 Photographic plates

The traditional method of recording astronomical images was to expose photographic plates or film.

Advantages:

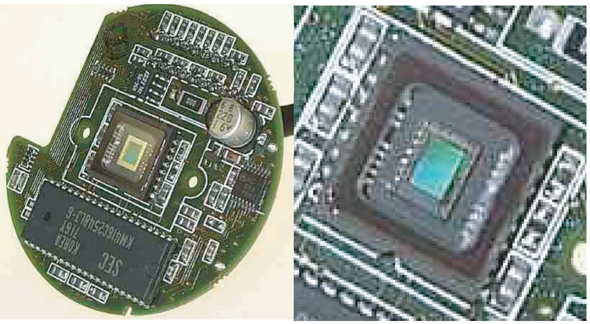
- Able to intensify images by long exposure.
- Able to store the results of observations for long periods.

Disadvantages:

- They are not efficient. The chemical processes that correspond to exposing film or plates use only about 1 percent of the incident light in forming the image.
- Photographic plates store data in analog format, whereas modern data processing with computers usually requires data in digital format

8.2.2 Charge-coupled devices (CCD)

Modern astronomical observations rely heavily on the electronic components called charge-coupled devices (CCDs) to record images (see following figure). These are electronic chips having light-sensitive elements (pixels) that can be used to produce a digital image that can be recorded by computers.



Charge-coupled device

In these devices particles of light (photons) generate electrons that are stored and can be counted, with the number of electrons proportional to the amount of light.

Advantages:

- More efficient than photographic plates (as high as 70 percent efficiency, compared with about 1 percent for photographs)
- More faithful indicators of the intensity of collected light than are photographs.
- Their directly digital nature makes them more suited for modern data analysis using computers.

8.2.3 Spectrographs

Spectrographs separate the light from stars and other objects according to wavelength in order to produce a spectrum. Modern spectrographs commonly use a diffraction grating to produce the spectrum.

Spectra produced by spectrographs were typically recorded using photographic plates in earlier times; in modern observations, spectra are primarily recorded using CCD technology.

8.2.4 Computers

Computers are used in astronomy in three broadly different senses.

1. The control of large telescopes and the acquisition of the data.
2. Solution of large mathematical models in theoretical astronomy.
3. Distributing astronomy information and data over the Web, and in astronomy educational technology.

8.3 Radio Frequency Observations

The first nonvisual spectral region that was used extensively for astronomical observations was the radio frequency (RF) band. Telescopes observing at these wavelengths are commonly called *radio telescopes.*

Since most frequency ranges of RF radiation penetrate the atmosphere well, radio telescopes are not as restricted in their locations as their optical counterparts. They need not be on tall mountains, and need not be in dry areas since radio waves penetrate clouds. It is desirable for them to be shielded from as much local radio interference as possible, which favors secluded valleys.

The Arecibo Radio Telescope

Because radio telescopes deal with long-wavelength radiation, their resolution is intrinsically poor. Thus, most radio telescopes are large. The largest in the world is the Arecibo Observatory, shown below, which has a 305-meter dish set in a hillside in Puerto Rico.

The Arecibo Radio Observatory

8.3.1 The 21-cm neutral hydrogen line

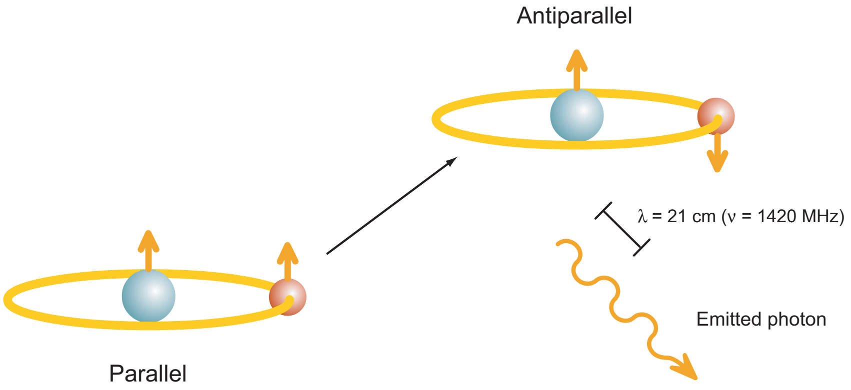
In neutral hydrogen (H I) the proton and electron can be imagined to spin like tops with their spin axes either parallel or antiparallel.

Neutral hydrogen atom (H I)

Parallel spin configuration
(higher energy)

Antiparallel spin configuration
(lower energy)

When hydrogen atoms switch from the parallel to the antiparallel configuration, they emit radio waves with a wavelength of 21 centimeters and a corresponding frequency of exactly 1420 MHz.



This is called the *21-cm line*, and it occurs in the RF part of the spectrum.

The 21-cm line can be seen only in cold, low-density clouds of neutral atomic hydrogen (H I). In hotter, denser clouds the hydrogens collide too often to permit the 21-cm photon to be radiated before something else happens to the atom.

Lifetime of the Parallel-Spin State

On the average, a hydrogen atom with spins parallel will live for 11 million years before it emits a 21-cm photon and flips to the lower-energy antiparallel state. But there is so much neutral hydrogen that the 21-cm line is very common in RF observations.

8.3.2 Long-baseline interferometers

Recall from Eq. (41) that the minimum angle that a telescope can resolve is about

$$\alpha = 2.516 \times 10^5 \left(\frac{\lambda}{d}\right) \text{ arc seconds}$$

because of diffraction effects. Therefore,

- The larger the diameter d, the better the resolution.
- The longer the wavelength λ the poorer the resolution.

Since radio waves have very long wavelength, radio telescopes have intrinsically low resolution unless they are very large. Even the largest single radio telescopes have resolutions comparable only to the diameter of the Sun on the sky ($\frac{1}{2}$ degree).

Estimate of Radio Telescope Resolution

For example, consider a 25 m dish with a wavelength of 21 cm. From the Rayleigh criterion, the diffraction limited resolution is

$$\begin{aligned}\alpha &= 2.5 \times 10^5 \left(\frac{\lambda}{d}\right) \text{ arc sec} \\ &= 2.5 \times 10^5 \left(\frac{0.2\text{ m}}{25\text{ m}}\right) \simeq 2000 \text{ arc sec} \simeq \tfrac{1}{2}^{\circ}.\end{aligned}$$

It is possible to use more than one radio telescope at separated locations and combine their signals electronically to have them function to some degree as if they were a single telescope.

- Such a device is called an *interferometer.*
- The corresponding resolution is dictated by the distance between the two telescopes (the *baseline*).
- This larger effective size is termed the *synthetic aperture*.

Radio telescopes have intrinsically low resolution because of the long wavelengths but radio interferometers may exceed optical telescopes in resolution because of their large effective size.

Examples of radio interferometers:

1. *Very Large Array (VLA)*: 27 radio telescopes each 25 meters in diameter in Socorro, New Mexico. Telescopes arrayed in a Y-shaped pattern up to 22 miles across.
2. *Very Long Baseline Array (VLBA)*: 10 radio telescopes, stretching from the Virgin Islands to Hawaii, with an effective diameter of more than 8000 km.

Estimated Resolutions for Interferometers

The VLA has a maximum baseline of 36.4 km. For 21 cm radiation, the diffraction limited resolution is then estimated as

$$\begin{aligned}\alpha &= 2.5 \times 10^5 \, (\lambda / d) \ \text{ arc sec} \\ &= 2.5 \times 10^5 \left(\frac{0.2 \text{ m}}{36.4 \times 10^3 \text{ m}} \right) \simeq 1.4 \text{ arc sec.}\end{aligned}$$

For the VLBA a corresponding calculation gives

$$\alpha = 2.5 \times 10^5 \left(\frac{0.2 \text{ m}}{8000 \times 10^3 \text{ m}} \right) \simeq 0.0006 \text{ arc sec.}$$

Better resultion is possible at shorter wavelengths. For reference the HST has a best resolution of about $0.05''$.

In astronomy, we often have to deal with very small angles because of the very large distances involved (recall how small parallax angles for stars are, for example). In this case we can often simplify the trigonometry by *small-angle formulas.*

Small-Angle Formulas

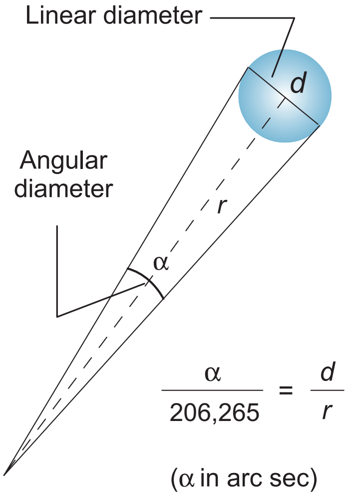
In trigonometry, if we have "long, skinny triangles" (one angle is very small), we can approximate for the small angle θ

$$\sin\theta \simeq \theta \qquad \cos\theta \simeq 1$$

(angles expressed in radians). For example, suppose an angle of $\theta = 1^\circ = \pi/180$ rad $= 0.017453$ rad. Then

$$\sin(\theta) = 0.01752 \simeq \theta \qquad \cos\theta = 0.99985 \simeq 1.$$

and the approximation gets better for smaller angles. This is often an excellent approximation in astronomy where we may be dealing with triangles having one very short leg and two very long legs. Then we have from trigonometry simplified using the small-angle approximation:



where the distances d and r are expressed in the same units and the angle α is expressed in arc sec.

How Good is 0.0002 Arc Sec Resolution?

Under some conditions the VLBA is capable of 0.0002 arc sec resolution. Let's use the small-angle formula to see what this means.

Suppose we want to be able to read a newspaper with letters about 2 mm $=$ 0.002 m high. If our resolution in arc sec is α, then the maximum distance at which we could resolve the letters in the newspaper is

$$r = 206,265d\left(\frac{\text{arc sec}}{\alpha}\right). \tag{42}$$

taking $d = 0.002$ m and $\alpha = 0.0002$ arc sec,

$$\begin{aligned} r &= (206,265)\left(\frac{0.002\text{ m}}{0.0002}\right) \\ &= 2.06 \times 10^6\text{ m} \\ &\simeq 2000\text{ km}. \end{aligned}$$

So with 0.0002 arc sec resolution we could read a newspaper in New York while sitting in Chicago!

In a more practical astronomy application, the center of our galaxy is about

$$r = 8.5\text{ kpc} \simeq 28,000\text{ ly} \simeq 1.75 \times 10^9\text{ AU}$$

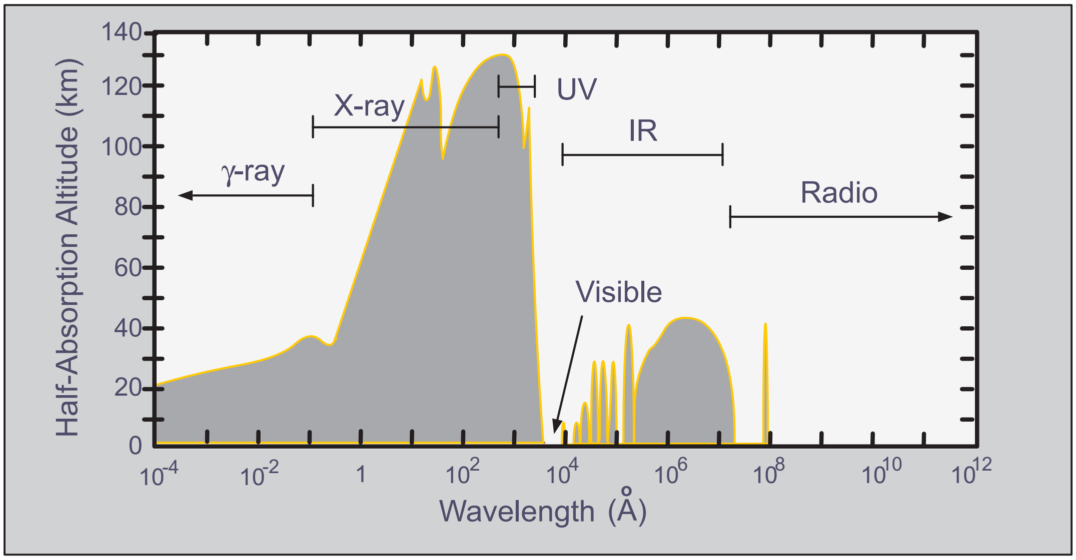
away (that is, about a billion times further away than the Sun). How large a horizontal distance d can we resolve with the VLBA at the center of the galaxy if its resolution is 0.0002 arc sec? Rearranging Eq. (42) above,

$$\begin{aligned} d &= \frac{r}{206,265}\left(\frac{\alpha}{\text{arc sec}}\right) \\ &= \frac{(1.75 \times 10^9\text{ AU})(0.0002)}{206,265} \\ &= 1.7\text{ AU}. \end{aligned}$$

So with the VLBA we could resolve a region approximately the volume of the Earth's orbit at the center of the galaxy.

8.4 Space-Based Telescopes

Recall our earlier discussion of *atmospheric windows:*



Only visible, RF, and some IR are easily seen from within the atmosphere. Wavelengths requiring platforms above all or most of atmosphere:

- γ-ray
- X-ray
- UV
- IR

In addition, even for regions like visible that penetrate the atmosphere, the intrinsic resolution from space is much better because of no distorting atmosphere.

Real-time position of some orbiting observatories (2D):
http://science.nasa.gov/Realtime/JTrack/Spacecraft.html

Real-time position of some orbiting observatories (3D):
http://science.nasa.gov/realtime/jtrack/3d/JTrack3D.html

Real-time simulated view from orbiting satellites:
http://www.fourmilab.to/earthview/satellite.html

Note the keyboard–mouse control options for things like zoom and orientation, and the buttons and drop-down menus that allow different cases to be selected.

8.5 Non-Electromagnetic Observations

Most, but not all, of our information in astronomy comes from detecting electromagnetic waves. Important examples of non-electromagnetic data include

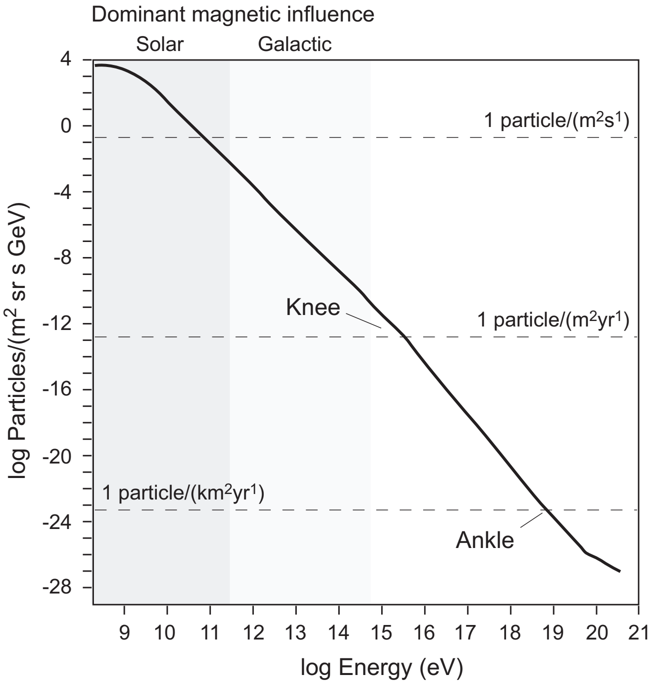
1. Cosmic rays
2. Neutrinos
3. Gravitational waves

8.5.1 Cosmic-ray detection

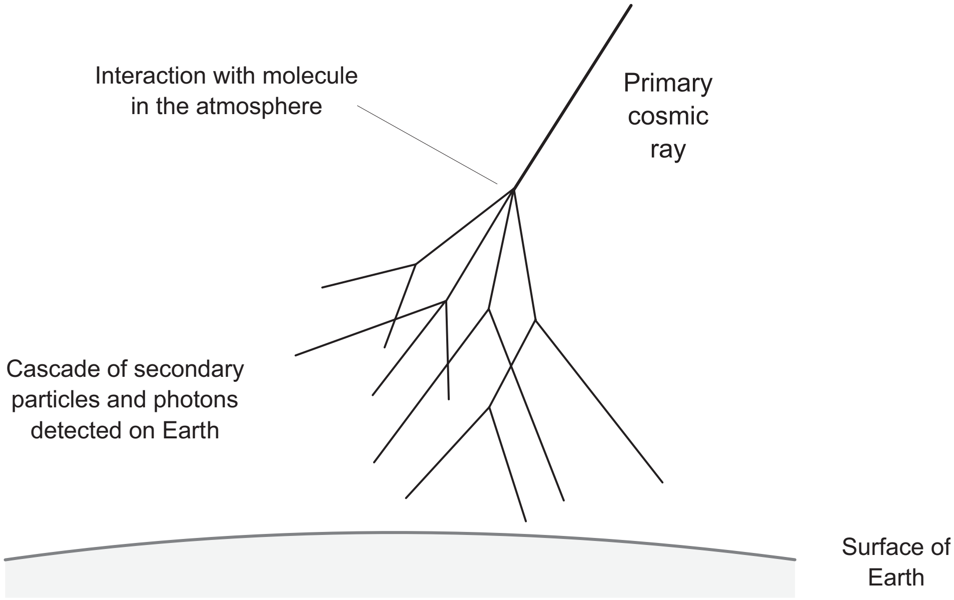
The Earth is being bombarded continuously by high-energy particles called *cosmic rays.* These are particles, such as protons and the nuclei of heavy atoms, travelling at near-light velocities.

Cosmic rays are the most energetic particles known in the Universe, with energies that can be 10^8 times larger than the greatest energy achieved in particle accelerators on Earth. The most energetic cosmic ray yet detected carry about 10^{20} eV. This is about the energy of a major-league fastball, but carried by a subatomic particle.

The spectrum of observed cosmic rays is summarized in the following figure.



Stages of a cosmic ray shower:



1. The cosmic rays smash into the nuclei of atmospheric atoms and produce many secondary particles. Because of their high velocity, these particles produce a characteristic light called Cerenkov radiation.
2. As the particles created in the original collision collide with other nuclei in the atmosphere, they produce additional particles and high-energy photons.
3. In the lower atmosphere, the cascade of particles slows sufficiently that most of the interaction with the atmosphere produces UV light through electronic excitations.

Detectors on Earth detect the secondaries and the light produced in the atmosphere. From these the event is reconstructed, giving properties of original cosmic ray.

Many cosmic rays are probably produced by the expanding debris from supernova explosions, but we don't understand very well where cosmic rays are produced. One reason for the uncertainty is that most cosmic rays carry electrical charges, which causes their motion to be altered by the magnetic field of the galaxy. Thus, if they come from very far away we cannot tell where they came from simply by noting their direction of motion when they strike the Earth.

8.5.2 Neutrino detection

An important new area of astronomy involves detection of one of the most common and yet most elusive particles of nature, *neutrinos.* Neutrinos are elementary particles without electrical charge and a very tiny mass.

> Every second 10^{12} neutrinos pass through your body, yet they interact so weakly with matter that you never notice it. They are so elusive that one of them can pass easily through a light-year of lead without a single interaction with the lead atoms.

If neutrinos interact so weakly, why are they so important?

1. Solar neutrinos detected on Earth offer us a direct snapshot of the Sun's core, where the energy is produced.[2]
2. Neutrinos are important to our understanding of the early Universe (near the time of the big bang when the Universe was created).
3. Neutrinos are produced in huge amounts by violent events like supernova explosions. They may play central roles in the mechanism responsible for the event and may carry important diagnostic information if detected.

> **Gold Mines and Cleaning Fluid**
>
> The first systematic study of neutrinos coming from the sky used a 100,000-gallon tank of dry cleaning fluid nearly a mile underground in the Homestake Goldmine in South Dakota. About once every three days, a chlorine atom was converted by interaction with a neutrino to an argon atom in this tank, and clever chemistry was used to allow these argon atoms to be counted when they underwent radioactive decay.

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[2] At one time there was thought to be a serious discrepancy between the number of neutrinos that we expect the Sun to produce and the number actually detected. We now know that this discrepancy is caused by newly-understood properties of neutrinos called *neutrino oscillations* that are associated with their having a tiny but non-zero mass.

Modern Neutrino Detectors

Modern neutrino dectors like the Sudbury Neutrino Detector (SNO) in Canada, and Super-Kamiokande (Super-K) in Japan, are filled with large volumes of water.[a] The detection is done by looking for the faint light emitted when neutrinos moving at or near the speed of light interact with the water (rather than by using chemistry techniques like in the original experiment). This allows much more information about the neutrinos to be determined than was possible before.

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[a] SNO uses both regular water and *heavy water,* which is water in which the more common mass-1 isotope of hydrogen has been replaced by the mass-2 isotope, which is called *deuterium.*

Neutrino detectors are located deep underground in sites like active mines. Why? Because they must be shielded from cosmic rays, which would produce a background of signals that would drown out the neutrino events. So neutrino astronomers get as far *away* from the sky as possible!

8.5.3 Gravitational wave detection

The electromagnetic field can have waves in it that carry energy and that we call light. Likewise, the gravitational field can have waves that carry energy and are called *gravitational waves.*

Gravitational waves may be thought of as ripples in space itself that travel at the speed of light. They have been detected indirectly from the properties of an object called the Binary Pulsar (which will be discussed in Astronomy 218), but have yet to be detected directly.

We believe that the Universe is full of gravitational waves, but they are very hard to detect because they interact very weakly. Several large gravity-wave detectors are currently running or on the drawing boards. One is LIGO (Laser Interferometry Gravitational-Wave Observatory), which has two parts, one in Louisiana and one in the state of Washington.

The Magnitude of the Problem

In detectors like LIGO, very sensitive instrumentation (which measures interference between laser beams) is used to detect the tiny motion of test masses caused by a passing gravitational wave. It is estimated that the measurable effect corresponds to a change of one part in 10^{21-22}. To set that in perspective, the distance to α-Centauri is 4.4 ly or about 4.2×10^{16} m. The distance corresponding to 10^{-21} of that is 4.2×10^{-5} m, which is about the width of a human hair.[a]

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[a] This is equivalent to 42 μ-meters; most human hair is 10-100 μ-meters thick.

Likely Strong Sources of Gravitational Waves:

- Collapse of the core of a massive star to a neutron star or black hole (core-collapse supernova)
- Merging neutron stars or black holes

Importance of Gravitational Waves

Gravitational waves are important because:

1. Only classic prediction of general relativity not yet directly confirmed (it has been confirmed indirectly through the Binary Pulsar).
2. Carries information about violent gravitational events such as formation of black holes.
3. Is the probe that in principle carries information from the earliest times relative to the big bang.

There is optimism that gravitational waves may be observed directly by detectors like LIGO within a decade.