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Astrophysical information

In observational astronomy we study the processes by which Earth-bound astronomers obtain and interpret information about distant parts of the universe. Theoretical descriptions of the natural world and observational/experimental data are complementary, and their interplay is a fundamental feature of scientific inquiry. For progress in astronomy we need extensive, sensitive, and accurate observations. But such data do not come for free. They are not just lying around for anybody to pick up. Work is required. An observer who simply accepts data at face value is likely to encounter problems.

In studying the observational process it will be helpful to adopt the following point of view. There is something we will call information which is present in an astronomical source. This information leaves the source, perhaps in the form of electromagnetic radiation. As it travels from the source to the observer it passes through intervening regions, often being modified in the process. The information then reaches the detection system. This final stage inevitably involves significant modification of the information. Noise is added, much information is lost, and other changes occur. From this final state the astronomer attempts to infer characteristics of the original source.

1.1 Electromagnetic radiation

The most important carrier of astronomical information is electromagnetic radiation. The electromagnetic spectrum is commonly broken down into various wavelength bands, as indicated in Table 1.1. Each band may be roughly described by both a characteristic photon energy $h\nu$ and a characteristic temperature $h\nu/k$. Each band carries a different set of information, since radiation at different wavelengths is produced (and modified) by different physical processes. And in each band the information is carried in a variety of forms (spectral, temporal, spatial, polarization, intensity).
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Table 1.1. Characteristic photon energies and temperatures

<table>
<thead>
<tr>
<th>Band</th>
<th>$E_{\text{typ}}$ (eV)</th>
<th>$T_{\text{typ}}$ (eV/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>gamma ray</td>
<td>$10^5$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>x-ray</td>
<td>$10^3$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>ultraviolet</td>
<td>$10$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>visible</td>
<td>$1$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>infrared</td>
<td>$0.1$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>microwave</td>
<td>$10^{-3}$</td>
<td>$10$</td>
</tr>
<tr>
<td>radio</td>
<td>$10^{-6}$</td>
<td>$0.01$</td>
</tr>
</tbody>
</table>

The wide range of wavelengths implies, among other things, that a wide variety of detection mechanisms must be employed. We will focus on the basic methods of detection and then provide some detail about differences between the bands. We will also discuss limitations to sensitivity and spatial resolution and how these vary between bands. Similarly, each wavelength band will have its own characteristics associated with each type of analysis. Here again we will focus on the fundamentals of the various types of analysis (spectroscopy, high speed photometry, imaging, polarimetry, photometry), providing some detail about how these types of analysis vary between the different bands.

1.2 Other carriers of information

In addition to electromagnetic radiation we have information carried to us via neutrinos, cosmic rays, and gravitational waves. These will be discussed in Chapters 14, 15, and 16, respectively. The study of material such as meteorites, lunar rocks, and interplanetary dust particles, although important, is somewhat specialized and will not be discussed here. The possible future detection of exotic particles such as dark matter will also not be discussed.

Neutrinos have been detected both from the Sun (at characteristic energies of $\sim 10^5$ eV) and from supernovae ($\sim 10^7$ eV). They contain information in their flux, in their arrival times (in the case of supernovae), and in their spectra. The lower than expected flux of neutrinos from the solar core was a longstanding problem in astrophysics, now considered to be resolved. The discovery of neutrinos from SN 1987A provided important confirmation of our picture of core-collapse supernovae.

Studies of neutrino energy spectra have been difficult due to the fact that detectors are typically sensitive to neutrinos of particular energies determined by the type of interaction material used (gallium, chlorine, etc.).

Cosmic rays consist of energetic electrons, protons, and heavy nuclei (out to Pb and beyond), reaching Earth from distant astrophysical sources. The lower energy
1.3 Intervening regions

Particles may be detected directly from balloons and satellites. The higher energy particles range up to about $10^{20}$ eV. These create extensive air showers in Earth’s atmosphere which can be detected with ground arrays sensitive to fluorescence from atmospheric nitrogen. Studies of the relative abundances of cosmic ray particles and their energy spectra reveal information about cosmic composition and the energetics of the generating sources (e.g. pulsars).

Gravitational waves from astrophysically interesting events are predicted with strains of

$$\delta L/L \lesssim 10^{-23}. \quad (1.1)$$

Current instruments such as LIGO and Virgo are approaching this level in the 100 Hz range.

1.3 Intervening regions

We speak of astronomy as an observational (not an experimental) science, implying that generally we do not have control over the conditions of our experiment and cannot directly probe or manipulate the object of interest. A corollary fact is that there exist intervening regions which can affect the flow of information from an astronomical source to the observer. These intervening regions include the intergalactic, interstellar, and interplanetary mediums and Earth’s atmosphere. The effects of such regions on the flow of information are understood only in part. The intergalactic, interstellar, and interplanetary mediums are themselves astronomical entities about which we have limited observational information. And although we have abundant information about global properties of Earth’s atmosphere, we generally lack sufficient detail down to the smallest relevant spatial scales (centimeters) and time scales (milliseconds).

There are situations in astrophysics in which the intervening region is itself the object of interest. Examples include galactic H I (21 cm) absorption, quasar (Ly α) absorption line systems, gravitational lensing and micro-lensing studies, and the Sunyaev–Zel’dovich effect. In these cases some knowledge about the background sources of radiation is required in order to study the effects produced by the intervening regions. For simplicity we will concentrate here on the more common case, in which one wishes to study a distant object and the intervening regions have the ability to modify the flow of radiation from the object to the observer.

1.3.1 Intergalactic/interstellar medium

The interstellar (and intergalactic) medium (ISM/IGM) contains gas and dust. Dust particles absorb and scatter light. If the size, shape, and composition of the dust grains were known, their effect on electromagnetic radiation could, in principle,
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be calculated (Mie, 1908; van de Hulst, 1957). But these properties are not readily determined and must be inferred from global characteristics such as the wavelength dependent coefficients of absorption and scattering, which may be different for different lines of sight through the Galaxy. The combined effect of scattering and absorption is referred to as extinction. The average value of extinction due to dust in the plane of the Galaxy is

\[ \langle A_V \rangle / D \approx 2 \text{ mag kpc}^{-1}. \]  

Interstellar extinction is dependent on wavelength. Since extinction is stronger in the blue portion of the visible spectrum, starlight is reddened as it passes through the ISM. A typical value for the reddening in the plane of the Galaxy (the differential extinction between the B and V photometric bands) is

\[ \langle E_{B-V} \rangle / D \approx 0.6 \text{ mag kpc}^{-1}. \]  

Interstellar reddening is likely to be highly dependent on the nature of the dust particles and thus variable from one region to another.

Atomic (neutral) gas in the ISM/IGM can produce various interstellar absorption lines. There is strong absorption shortwards of the Lyman limit (91 nm) due to neutral hydrogen (H I).

The ionized ISM/IGM (plasma) gives rise to effects such as pulsar dispersion, Faraday rotation, and radio scintillation. Pulsar dispersion is parameterized by the dispersion measure,

\[ DM = \int_{0}^{L} n_e \, dl, \]  

which is typically of order 10–100 parsec cm\(^{-3}\) for lines of sight towards nearby pulsars. Relative to a signal at sufficiently high frequency, a lower frequency \( \nu \) will be delayed by a time

\[ \Delta t = \frac{e^2}{2\pi m_e c} \frac{1}{\nu^2} DM. \]  

Faraday rotation is parameterized by the rotation measure,

\[ RM = \int_{0}^{L} n_e \, H_\parallel \, dl, \]  

with the convention that RM and \( H_\parallel \) are positive for magnetic fields pointing towards us. Typical values of the galactic magnetic field are of order a few \( \mu \text{G} \). In traversing a region of rotation measure \( RM \), a linearly polarized wave will have its plane of polarization rotated by an angle
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\[ \Delta \theta = \frac{e^3}{2 \pi m_e c^2} \frac{1}{v^2} \nu^2 \theta_M, \]  

(1.7)
counterclockwise as viewed by us for positive RM.

Cosmic ray particles are also influenced by the medium they pass through. The lower energy cosmic rays follow magnetic field lines, making it impossible to determine their point of origin. The higher energy cosmic rays interact with the photons of the microwave background radiation. Since they lose energy in these interactions, the highest energy cosmic rays that we see must have originated within about 50 Mpc of Earth.

1.3.2 Interplanetary medium

There also exists an interplanetary medium consisting of gas and dust, which can produce effects similar to the interstellar medium. The interplanetary medium is concentrated in the plane of the solar system. The zodiacal dust is evident by its scattering and absorption and, since it is warm, also by its thermal emission in the infrared. The plasma in the solar corona and solar wind influence the propagation of radio waves (Thompson et al., 2001). Such effects vary with the 11-year solar activity cycle and on shorter time scales as well.

1.3.3 Earth’s atmosphere

The Earth’s atmosphere produces a multitude of effects, most of which interfere strongly with the free propagation of astronomical signals. Molecules and atoms in the atmosphere absorb radiation across almost the entire electromagnetic spectrum except in the visible and radio bands. Atmospheric dust produces scattering of visible light, the amount of which is very much dependent on such things as volcanic activity and wind patterns (e.g. dust from the Sahara). And of course there is variable cloud cover. The upper atmosphere emits radiation by a process known as airglow. The ionosphere cuts off the propagation of long wavelength radio waves. As with most ionospheric phenomena, this cutoff is dependent on the solar activity cycle. And finally, turbulence in the atmosphere gives rise to the effects known as seeing and scintillation.

Radio and microwave absorption

The radio, microwave, millimeter, and submillimeter wave bands extend out to frequencies of several hundreds of GHz, as shown in Figure 1.1. The atmospheric spectrum in this region contains many discrete rotational lines of molecules such as oxygen (O₂), water vapor (H₂O), and to a lesser extent ozone (O₃) and other
trace constituents. At the shorter wavelengths the water vapor lines blend into a quasi-continuous absorption.

The oxygen lines are magnetic dipole transitions and arise throughout the troposphere. The tropospheric pressure distribution is determined by hydrostatic equilibrium and is roughly exponential,

\[ P(z) = P_0 e^{-z/H}, \]  

(1.8)

with a scale height

\[ H = \frac{kT}{\langle \mu \rangle m_{\text{Hg}}}, \]  

(1.9)

which is of order 7 km for a typical temperature of \( T = 250 \) K and a mean molecular weight \( \langle \mu \rangle = 29 \). Most molecular species follow this exponential distribution.

Water vapor, on the other hand, is not well mixed. The saturation vapor pressure of water vapor is a strong function of temperature. In the troposphere, temperature drops with altitude, and colder air has a strongly reduced water vapor content. The distribution of water vapor is quasi-exponential, with a reduced scale height of

\[ H_{\text{H}_2\text{O}} \approx 2–3 \text{ km}. \]  

(1.10)

The profiles of tropospheric absorption lines are determined by pressure broadening. Therefore, most atmospheric line profiles are approximately Lorentzian in shape with very broad wings. Since the water vapor is preferentially present in the lower layers of the atmosphere, water vapor line widths are typically broader than...
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Figure 1.2 Detail of atmospheric transmission from 480 to 500 GHz for 0.01 mm precipitable water vapor, showing the presence of weak, narrow ozone lines. The lower curve (red in electronic edition) corresponds to an altitude of 5108 m. At an aircraft altitude of 12.5 km (upper, blue curve), the effect of pressure broadening is much less and atmospheric transmission can approach 98% near 492 GHz. Courtesy of Atacama Pathfinder Experiment (APEX).

those of other atmospheric constituents. By the same token, lines formed at high altitudes, such as those of ozone, are narrow, as shown in Figure 1.2. Water lines get considerably narrower wings when observed at high altitudes.

Lorentzian line shape

The quantum mechanical problem of the line shape for absorption or emission by an atom undergoing random collisions (Gross, 1955) is somewhat subtle. But for our present purposes we will treat it as analogous to a classical simple harmonic dipole oscillator with radiative damping, which exponentially decays (for \( t \geq 0 \)),

\[
x(t) = x_0 e^{-\Gamma t/2} \cos 2\pi \nu_0 t.
\]  

(1.11)

The \((-i)\) Fourier transform of \( x(t) \) is

\[
\hat{x}(\nu) = \frac{x_0}{2i} \left( \frac{1}{2\pi \nu - 2\pi \nu_0 - i\Gamma/2} + \frac{1}{2\pi \nu + 2\pi \nu_0 - i\Gamma/2} \right),
\]  

(1.12)

the second term of which can be generally neglected. The total radiated power is given by the Larmor formula. In mks units

\[
P = \frac{1}{4\pi \varepsilon_0} \frac{2q^2 \hat{x}^2}{c^3}.
\]  

(1.13)
According to Rayleigh’s theorem the intensity profile $I(\nu)$ is proportional to $|\hat{x}(\nu)|^2$, so the radiated power is distributed in frequency according to the Lorentzian profile

$$\phi(\nu) \approx \frac{1}{4\pi} \frac{\Gamma}{(2\pi \nu - 2\pi \nu_0)^2 + (\Gamma/2)^2},$$

which for $\Gamma \ll \nu_0$ can be normalized for unit area as

$$\phi(\nu) \approx \frac{1}{\pi} \frac{\gamma}{(\nu - \nu_0)^2 + \gamma^2}.$$

The HWHM line width $\gamma$ is proportional to the rate of collisions.

**Infrared absorption and background**

The infrared spectrum is dominated by absorption from CO$_2$ and H$_2$O. Water vapor is a particular problem because the water molecule is an asymmetric top with a permanent dipole moment. These and other molecular lines leave the atmosphere totally opaque at many infrared wavelengths. Between the absorption bands there are a few discrete windows which are sufficiently transparent to allow ground-based observations. The best of these windows are centered near 1.2, 2.2, 3.4, 5.0, 10, and 20 $\mu$m. However, even in these bands ground-based observations are faced with strong atmospheric thermal background emission, especially near 5, 10, and 20 $\mu$m (near the peak of a blackbody spectrum for room temperature).

There is therefore a strong incentive for space-based observations throughout the infrared, but especially for those portions of the spectrum with significant atmospheric opacity. An extensive infrared satellite survey was conducted by the IRAS satellite, which measured long wavelength fluxes (12, 25, 60, 100 $\mu$m), albeit with low spatial resolution. More recent work was done by ISO, a satellite launched by the European Space Agency (ESA). The most important current infrared satellites are Spitzer (SIRTF) and Herschel (FIRST), which have both imaging and spectroscopic capabilities. SOFIA, an airborne telescope built jointly by Germany and the USA is also about to start producing data.

**Low frequency EM wave propagation**

Consider a free electron plasma of density $N$ in a field $\mathbf{E}_0 e^{-i2\pi vt}$. Neglecting collisions, the equation of motion for an electron displacement is

$$m \frac{d^2\mathbf{x}}{dt^2} = e \mathbf{E}_0 e^{-i\omega t}.$$

(1.16)
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Solving for the electron velocity and current density, we get

\[
\vec{v} = \frac{d\vec{x}}{dt} = \frac{-e}{im_0} \vec{E}_0 e^{-i\omega t}, \tag{1.17}
\]

\[
\vec{J} = Ne\vec{v} = -\frac{Ne^2}{im_0} \vec{E}_0 e^{-i\omega t}. \tag{1.18}
\]

Since the conductivity of a material is defined by \( \vec{J} = \sigma \vec{E} \), the conductivity of the electron plasma is

\[
\sigma = i \frac{Ne^2}{m_0 \omega}. \tag{1.19}
\]

Waves in a conducting medium propagate according to the damped wave equation

\[
\nabla^2 \vec{E} - \epsilon \mu \frac{\partial^2 \vec{E}}{\partial t^2} - \sigma \mu \frac{\partial \vec{E}}{\partial t} = 0. \tag{1.20}
\]

Adopting a trial solution of \( \vec{E} = \vec{E}_0 e^{(i\tilde{k}z - \omega t)} \), we can get

\[
\tilde{k}^2 = \frac{\omega^2}{c^2} \left( \frac{\epsilon}{\epsilon_0} + i \frac{\sigma}{\epsilon_0 \omega} \right) \tag{1.21}
\]

\[
\approx \frac{\omega_p^2}{c^2} \left( 1 - \frac{\omega^2}{\omega_p^2} \right), \tag{1.22}
\]

where \( \omega_p^2 = \frac{Ne^2}{m_0 \epsilon_0} \). For \( \omega < \omega_p \), the wavenumber \( \tilde{k} \) is imaginary, so waves are exponentially attenuated, not propagated. In the ionosphere electron densities are of order \( 10^6 \text{ cm}^{-3} \), so frequencies below about 10 MHz are not propagated. The exact cutoff frequency varies with the day/night cycle and with solar activity.

**Airglow**

An additional factor to consider at visible and near-visible wavelengths is airglow, a form of fluorescent recombination which occurs in the upper atmosphere (~100 km). In the visible, strong airglow lines of O I occur at 558 and 630 nm, O II at 762 nm, etc. The intensity of telluric airglow is measured in units of rayleighs,

\[
1 \text{ rayleigh} = 10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \tag{1.23}
\]

\[
= 1.58 \times 10^{-11}/\lambda \text{ nm W cm}^{-2} \text{ sr}^{-1}. \tag{1.24}
\]

**Rayleigh scattering**

Atmospheric scattering (resonant, Rayleigh) is also a significant source of sky background in the ultraviolet, visible, and near-infrared. Consider a bound electron with a driving field. The equation of motion is
\[ \ddot{x} + \Gamma \dot{x} + \omega_0^2 x = \frac{e}{m} E_0 \cos \omega t, \quad (1.25) \]

which, for a trial solution
\[ x = x_0 e^{i \omega t}, \quad (1.26) \]
gives an amplitude displaying a resonant response where
\[ x_0 = \frac{e}{m} E_0 \frac{1}{\omega^2 - \omega_0^2 - i \omega_0 \Gamma}, \quad (1.27) \]

Calculating the radiated power by the Larmor formula gives
\[ P = \frac{1}{4 \pi \epsilon_0} \frac{2 q^2}{3 c^3} \omega^4 |x_0|^2. \quad (1.28) \]

We get the interaction cross section by normalizing by the incident Poynting flux,
\[ \sigma(\omega) = \sigma_T \frac{\omega^4}{(\omega^2 - \omega_0^2)^2 + (\omega_0 \Gamma)^2}, \quad (1.29) \]
\[ \sigma_T = \frac{2}{3} \frac{q^4}{m^2 c^4} \frac{1}{4 \pi \epsilon_0^2}. \quad (1.30) \]

At low frequencies this displays the \( \omega^4 \) Rayleigh scattering and at high frequencies the constant Thomson cross section \( \sigma_T \), with the resonant fluorescence peak in between, as shown in Figure 1.3.

**Atmospheric turbulence**

Atmospheric density inhomogeneities produce regions of different refractive indices which introduce wavefront corrugations, as shown in Figure 1.4. Seeing

![Figure 1.3 Scattering from bound electrons.](image-url)