Chapter 3

The Mechanisms of Electromagnetic Emissions

Objectives: Upon completion of this chapter, you will be able to describe the difference between thermal and non-thermal radiation and give some examples of each. You will be able to distinguish between thermal and non-thermal radiation curves. You will be able to describe the significance of the 21-cm hydrogen line in radio astronomy.

If the material in this chapter is unfamiliar to you, do not be discouraged if you don't understand everything the first time through. Some of these concepts are a little complicated and few non-scientists have much awareness of them. However, having some familiarity with them will make your radio astronomy activities much more interesting and meaningful.

What causes electromagnetic radiation to be emitted at different frequencies? Fortunately for us, these frequency differences, along with a few other properties we can observe, give us a lot of information about the source of the radiation, as well as the media through which it has traveled.

Electromagnetic radiation is produced by either thermal mechanisms or non-thermal mechanisms.

Examples of thermal radiation include

- Continuous spectrum emissions related to the temperature of the object or material.
- Specific frequency emissions from neutral hydrogen and other atoms and molecules.

Examples of non-thermal mechanisms include

- Emissions due to synchrotron radiation.
- Amplified emissions due to astrophysical masers.

Thermal Radiation

Did you know that any object that contains any heat energy at all emits radiation? When you're camping, if you put a large rock in your campfire for a while, then pull it out, the rock will emit the energy it has absorbed as radiation, which you can feel as heat if you hold your hand a few inches away. Physicists would call the rock a "blackbody" because it absorbs all the energy that reaches it, and then emits the energy at all frequencies (although not equally) at the same rate it absorbs energy.

All the matter in the known universe behaves this way.

Some astronomical objects emit mostly infrared radiation, others mostly visible light, others mostly ultraviolet radiation. The single most important property of objects that determines the radiation they emit is *temperature*.

In solids, the molecules and atoms are vibrating continuously. In a gas, the molecules are really zooming around, continuously bumping into each other. Whatever the amount of molecular motion occurring in matter, the speed is related to the temperature. The hotter the material, the faster its molecules are vibrating or moving.

Electromagnetic radiation is produced whenever electric charges accelerate—that is, when they change either the speed or direction of their movement. In a hot object, the molecules are continuously vibrating (if a solid) or bumping into each other (if a liquid or gas), sending each other off in different directions and at different speeds. Each of these collisions produces electromagnetic radiation at frequencies all across the electromagnetic spectrum. However, the amount of radiation emitted at each frequency (or frequency band) depends on the temperature of the material producing the radiation.

It turns out that the shorter the wavelength (and higher the frequency), the more energy the radiation carries. When you are out in the sun on a hot day and your skin starts to feel hot, that heat is not what you need to worry about if you get sunburned easily. Most of the heat you feel is the result of infrared radiation striking the surface of your skin. However, it is the higher frequency—thus higher energy—ultraviolet radiation penetrating the skin’s surface that stimulates the deeper layers to produce the melanin that gives fair complected folks the nice tan—or bad sunburn. X-rays, at still higher frequencies, have enough energy to pass right through skin and other soft tissues. That is how bone and soft tissues of varying densities can be revealed by the x-ray imaging techniques used by medicine.

Any matter that is heated above absolute zero generates electromagnetic energy. The intensity of the emission and the distribution of frequencies on the electromagnetic spectrum depend upon the temperature of the emitting matter. In theory, it is possible to detect electromagnetic energy from any object in the universe. Visible stars radiate a great deal of electromagnetic energy. Much of that energy has to be in the visible part of the spectrum—otherwise they would not be visible stars! Part of the energy has to be in the microwave (short wave radio) part of the spectrum, and that is the part astronomers study using radio telescopes.

Blackbody Characteristics

Blackbodies thus have three characteristics:

1. A blackbody with a temperature higher than absolute zero emits some energy at all wavelengths.
2. A blackbody at higher temperature emits more energy at all wavelengths than does a cooler one.
3. The higher the temperature, the shorter the wavelength at which the maximum energy is emitted.

To illustrate, at a low temperature setting, a burner on an electric stove emits infrared radiation, which is transferred to other objects (such as pots and food) as heat. At a higher temperature, it also emits red light (lower frequency end of visible light range). If the electrical circuit could deliver enough energy, as the temperature increased further, the burner would turn yellow, or even blue-white.

The sun and other stars may, for most purposes, be considered blackbodies. So we can estimate temperatures of these objects based on the frequencies of radiation they emit—in other words, according to their electromagnetic spectra.

For radiation produced by thermal mechanisms, the following table gives samples of wavelength ranges, the temperatures of the matter emitting in that range, and some example sources of such thermal radiation.

Type of Radiation	**Wavelength Range (nanometers [10^{-9} m])**	**Radiated by Objects at this Temperature**	**Typical Sources**
Gamma rays	Less than 0.01	More than 10^8 K	Few astronomical sources this hot; some gamma rays produced in nuclear reactions
X-rays	0.01 - 20	10^6 - 10^8 K	Gas in clusters of galaxies; supernova remnants, solar corona
Ultraviolet	20 - 400	10^5 - 10^6 K	Supernova remnants, very hot stars
Visible	400 - 700	10^3 - 10^5 K	Exterior of stars
Infrared	10^3 - 10^6	10 - 10^3 K	Cool clouds of dust and gas; planets, satellites
Radio	More than 10^6	Less than 10 K	Dark dust clouds

The hotter the object, the shorter is the wavelength of the radiation it emits. Actually, at hotter temperatures, more energy is emitted at all wavelengths. But the peak amount of energy is radiated at shorter wavelengths for higher temperatures. This relationship is known as *Wien's Law.*

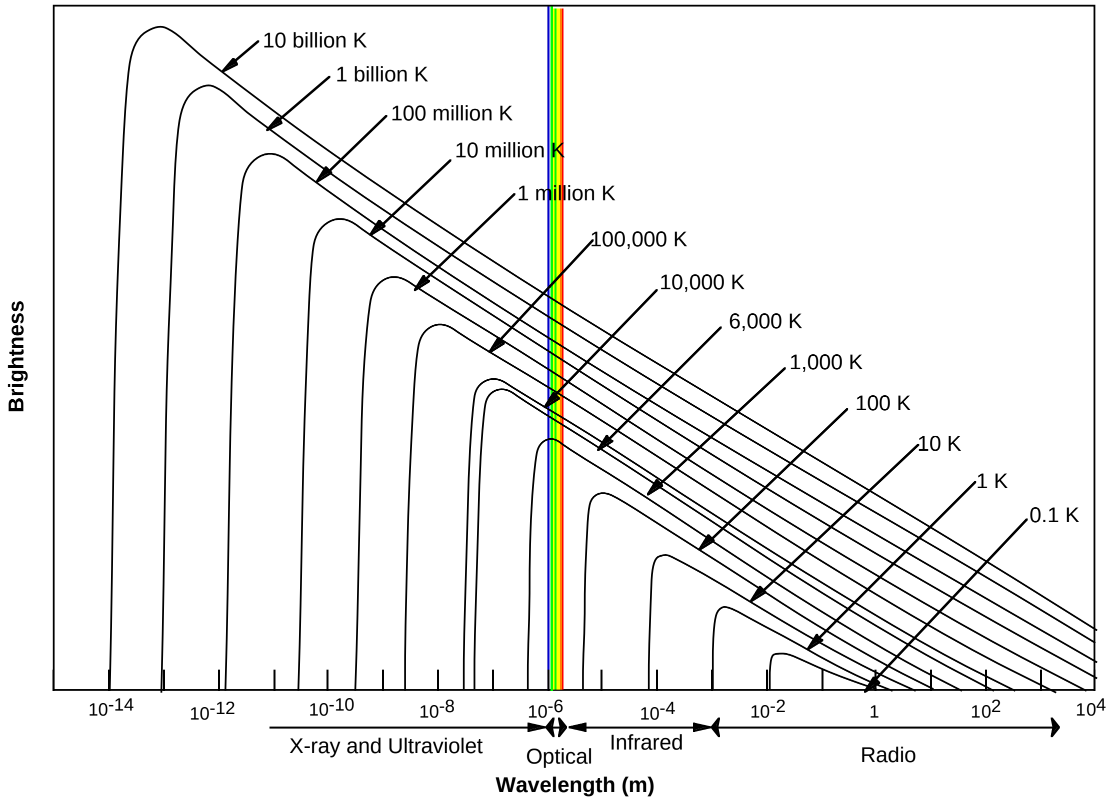
A beam of electromagnetic radiation can be regarded as a stream of tiny packets of energy called photons. *Planck's Law* states that the energy carried by a photon is directly proportional to its frequency. To arrive at the exact energy value, the frequency is multiplied by Planck's Constant, which has been found experimentally to be 6.625 x 10^{-27} erg sec. (The erg is a unit of energy.)

If we sum up the contributions from all parts of the electromagnetic spectrum, we obtain the total energy emitted by a blackbody over all wavelengths. That total energy, emitted per second per square meter by a blackbody at a given temperature is proportional to the fourth power of its absolute temperature. This relationship is known as the *Stefan-Boltzmann Law*. If the sun, for example, were twice as hot as it is and the same size, that is, if its temperature were 11,600 K, it would radiate 2^4, or 16, times more energy than it does now.

The *flux density* of the radiation is defined as the energy received per unit area per unit of frequency bandwidth. Astronomers also consider the radiation's *brightness*, which is a more mathematically precise calculation of the energy received per unit area, for a particular frequency bandwidth, and also taking into consideration the angle of incidence on the measuring surface and the solid angle of sky subtended by the source. The brightness of radiation received (at all frequencies) is thus related to temperature of the emitting object and the wavelength of the received radiation.

The variation of brightness with frequency is called the *brightness spectrum*. The *spectral power* is the energy observed per unit of time for a specific frequency bandwidth.

A plot of a brightness spectrum shows the brightness of the radiation received from a source as it varies by frequency and wavelength. In the plot below, the brightness of blackbodies at various temperatures is plotted on the vertical scale and wavelengths are plotted on the horizontal scale.



Brightness of Electromagnetic Radiation at Different Wavelengths for Blackbody Objects at Various Temperatures

The main thing to notice about these plots is that the curves never cross each other. Therefore, at any frequency, there is only one temperature for each brightness. So, if you can measure the brightness of the energy at a given frequency, you know the temperature of the emitting object!

Despite their temperatures, not all visible stars are good radio frequency emitters. We can detect stars at radio frequencies only

if they emit by non-thermal mechanisms (described next), or if they are in our solar system (that is, our sun), or

if there is gas beyond the star which is emitting (for example, a stellar wind).

As it turns out, the hottest and brightest stars emit more energy at frequencies above the visible range than below it. Such stars are known for their x-ray and atomic particle radiation. However, intense thermal generators such as our own sun emit enough energy in the radio frequencies to make them good candidates for radio astronomy studies. The Milky Way galaxy emits both thermal and non-thermal radio energy, giving radio astronomers a rich variety of data to ponder.

Our observations of radiation of thermal origin have two characteristics that help distinguish it from other types of radiation. Thermal radiation reproduces on a loudspeaker as pure static hiss, and the energy of radiation of thermal origin usually increases with frequency.

Continuum Emissions from Ionized Gas

Thermal blackbody radiation is also emitted by gases. Plasmas are ionized gases and are considered to be a fourth state of matter, after the solid, liquid, and gaseous states. As a matter of fact, plasmas are the most common form of matter in the known universe (constituting up to 99% of it!) since they occur inside stars and in the interstellar gas. However, naturally occurring plasmas are relatively rare on Earth primarily because temperatures are seldom high enough to produce the necessary degree of ionization. The flash of a lightning bolt and the glow of the aurora borealis are examples of plasmas. But immediately beyond Earth’s atmosphere is the plasma comprising the Van Allen radiation belts and the solar wind.

An atom in a gas becomes ionized when another atom bombards it with sufficient energy to knock out an electron, thus leaving a positively charged ion and a negatively charged electron. Once separated, the charged particles tend to recombine with their opposites at a rate dependent on the density of the electrons. As the electron and ion accelerate toward one another, the electron emits electromagnetic energy. Again, the kinetic energy of the colliding atoms tends to separate them into electron and positive ion, making the process continue indefinitely. The gas will always have some proportion of neutral to ionized atoms.

As the charged particles move around, they can generate local concentrations of positive or negative charge, which gives rise to electric and magnetic fields. These fields affect the motion of other charged particles far away. Thus, elements of the ionized gas exert a force on one another even at large distances. An ionized gas becomes a plasma when enough of the atoms are ionized so that the gas exhibits collective behavior.

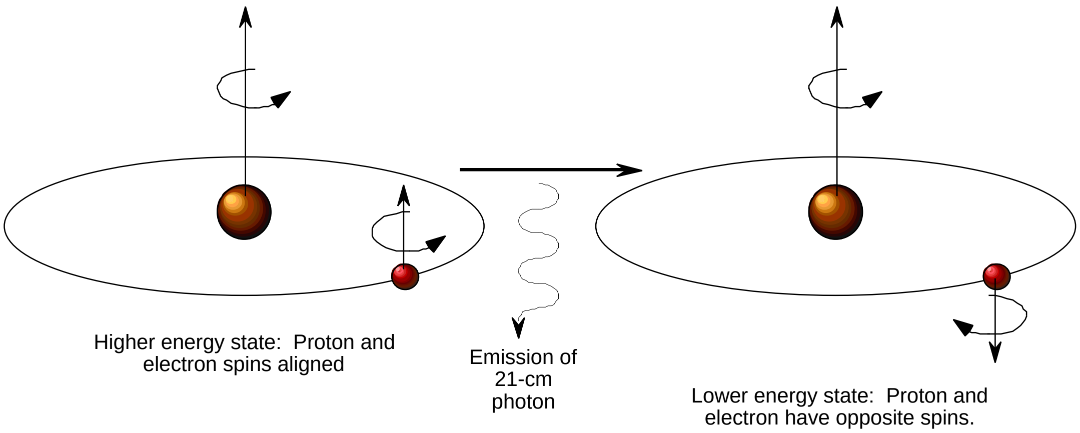
Whenever a vast quantity of free and oppositely charged ions coexist in a relatively small space, the combination of their reactions can add up to intense, continuous, wideband radio frequency radiation. Such conditions prevail around stars, nebulae, clusters of stars, and even planets—Jupiter being at least one we know of.

Spectral Line Emissions from Atoms and Molecules

While the mechanism behind thermal-related energy emissions from ionized gases involves electrons becoming detached from atoms, line emissions from neutral hydrogen and other atoms and molecules involves the electrons changing energy states within the atom, emitting a photon of energy at a wavelength characteristic of that atom. Thus, this radiation mechanism is called line emission, since the wavelength of each atom occupies a discrete “line” on the electromagnetic spectrum.

In the case of neutral (not ionized) hydrogen atoms, in their lower energy (ground) state, the proton and the electron spin in opposite directions. If the hydrogen atom acquires a slight amount of energy by colliding with another atom or electron, the spins of the proton and electron in the hydrogen atom can align, leaving the atom in a slightly excited state. If the atom then loses that amount of energy, it returns to its ground state. The amount of energy lost is that associated with a photon of 21.11 cm wavelength (frequency 1428 MHz).

Formation of the 21-cm Line of Neutral Hydrogen



Hydrogen is the key element in the universe. Since it is the main constituent of interstellar gas, we often characterize a region of interstellar space as to whether its hydrogen is neutral, in which case we call it an H I region, or ionized, in which case we call it an H II region.

Some researchers involved in the search for extra-terrestrial intelligence (see Chapter 8) have reasoned that another intelligent species might use this universal 21-cm wavelength line emission by neutral hydrogen to encode a message; thus these searchers have tuned their antennas specifically to detect modulations to this wavelength. But, perhaps more usefully, observations of this wavelength have given us much information about the interstellar medium and locations and extent of cold interstellar gas.

Recap

1. An object that absorbs and re-emits all energy that hits it without any reflections is a __________________.
2. The blackbody radiation from a hot object is (bluer/redder) __________________. than the blackbody radiation from a cooler object.
3. The hotter the object, the _______________ the wavelength of the peak range of blackbody radiation emitted.
4. Planck’s Law states that the amount of energy carried by a photon is directly proportional to its ___________________.
5. The total amount of energy at all wavelengths emitted by a blackbody, per square meter per second, is proportional to the ____________ power of the its absolute temperature.
6. A plot of a brightness spectrum displays the brightness of radiation received from a source at various ______________ or ___________________.
7. Electromagnetic radiation from blackbodies, ionized gas, and line emissions from atoms and molecules can all be generated by ________________ mechanisms.
8. Hot, ionized gases are called ______________.
9. Wavelengths of 21.11 cm are associated with line emissions from ________________ _______________.
10. Because blackbody curves do not cross, if you know the brightness of a blackbody at a given frequency, you also know its _________________.

1. blackbody 2. bluer 3. shorter 4 frequency 5. fourth 6. wavelengths, frequencies 7. thermal 8. plasmas 9. neutral hydrogen 10. temperature

For Further Study

- *Thermal radiation:* Kaufmann, 84-89.
- *Wien’s Law and Stefan-Boltzmann Law:* Kaufmann, 87-88, 197; Wynn-Williams, 28, App. G and H.
- *Planck’s constant*: Wynn-Williams, 12.
- *Plasmas:* Wynn-Williams, 43-54.
- *Spectral line emissions:* Kaufmann, 90-96; Morrison et al., 112-120.
- *21-cm emission line from neutral hydrogen:* Kaufmann, 460; Wynn-Williams, 30-42.

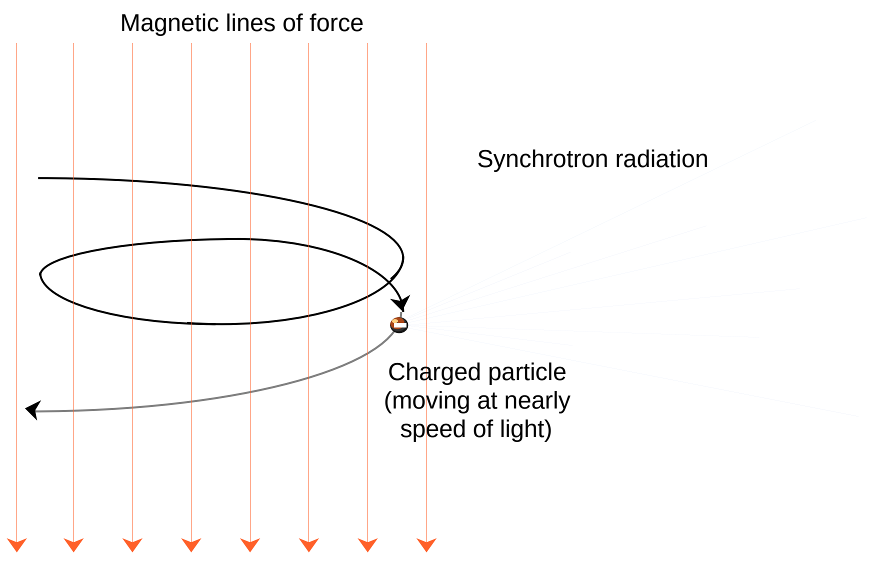
Non-thermal Mechanisms

Radiation is also produced by mechanisms unrelated to the temperature of object (that is, thermal radiation). Here we discuss some examples of non-thermal radiation.

Synchrotron Radiation

Notwithstanding the vast number of sources of thermal emissions, much of the radiation from our own galaxy, particularly the background radiation first discovered by Jansky, and most of that from other galaxies is of non-thermal origin. The major mechanism behind this type of radiation has nothing to do with temperature, but rather with the effect of charged particles interacting with magnetic fields. When a charged particle enters a magnetic field, the field compels it to move in a circular or spiral path around the magnetic lines of force. The particle is thus accelerated and radiates energy. Under non-relativistic conditions (that is, when particle velocities are well-below the speed of light), this *cyclotron radiation* is not strong enough to have much astronomical importance. However, when the speed of the particle reaches nearly the speed of light, it emits a much stronger form of cyclotron radiation called *synchrotron radiation*.

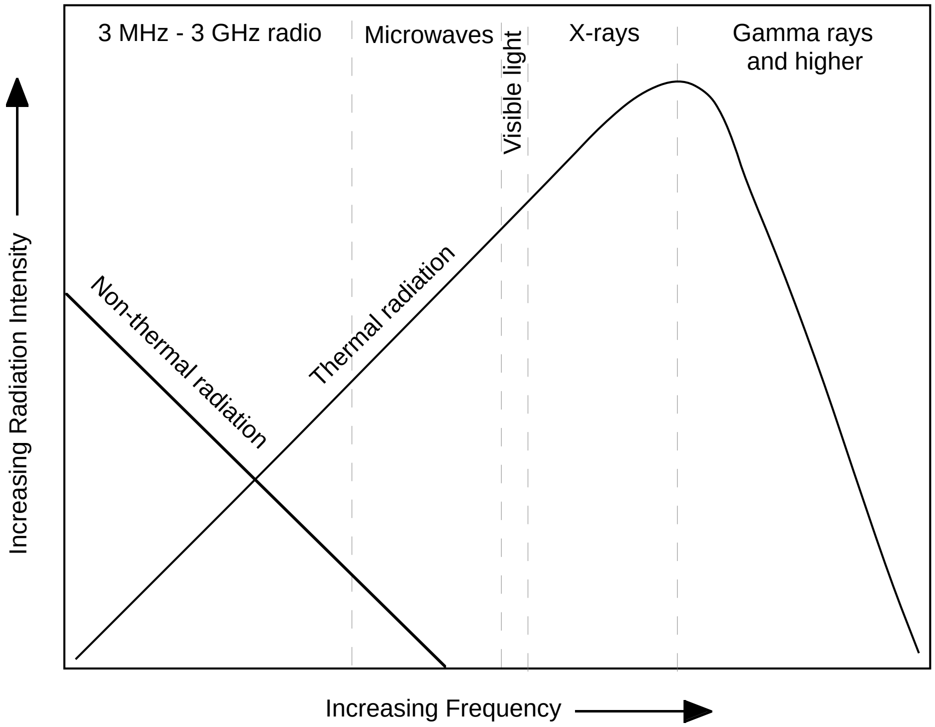
Emission of Synchrotron Radiation



Quasars (described in Chapter 6) are one source of synchrotron radiation not only at radio wavelengths, but also at visible and x-ray wavelengths.

An important difference in radiation from thermal versus non-thermal mechanisms is that while the intensity (energy) of thermal radiation *increases* with frequency, the intensity of non-thermal radiation usually *decreases* with frequency.

Relative Variation of Thermal and Non-thermal Radiation Emissions



Masers

Astronomical *masers* are another source of non-thermal radiation. “Maser” is short for m̲icro-wave-a̲mplified s̲timulated e̲mission of r̲adiation. Masers are very compact sites within molecular clouds where emission from certain molecular lines can be enormously amplified. The interstellar medium contains only a smattering of molecular species such as water (H_2O), hydroxl radicals (OH), silicon monoxide (SiO), and methanol (CH_3OH). Normally, because of the scarcity of these molecules, their line emissions would be very difficult to detect with anything but very crude resolution. However, because of the phenomenon of “masing,” these clouds can be detected in other galaxies!

In simplified terms, masing occurs when clouds of these molecules encounter an intense radiation field, such as that from a nearby source such as a luminous star, or when they collide with the far more abundant H_2 molecules. What is called a “population inversion” occurs, in which there are more molecules in an excited state (that is, their electrons have “jumped” to a higher energy level), than in a stable, ground state. This phenomenon is called *pumping*. As the radiation causing the pumping travels through the cloud, the original ray is amplified exponentially, emerging at the same frequency and phase as the original ray, but greatly amplified. Some masers emit as powerfully as stars! This phenomenon is related to that of spectral line emissions, explained in Chapter 4.

Incidentally, this same principle is used in a device called a maser amplifier, which is installed as part of some radio telescopes (not in the GAVRT, however) to amplify the signal received by the antenna.

Recap

1. ______________________ ____________________ is a non-thermal mechanism producing electromagnetic radiation by accelerating charged particles in a magnetic field to nearly the speed of light.
2. The intensity of non-thermal radiation often __________________ with frequency.
3. In the interstellar medium, areas within clouds of molecules that greatly amplify the radiation passing through them are called astrophysical ___________.

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1. synchrotron radiation   2. decreases   3. masers

For Further Study

- *Synchrotron radiation:* Wynn-Williams, 104, 108.
- *Masers:* Kaufmann, 378-379; Wynn-Williams, 95-97.