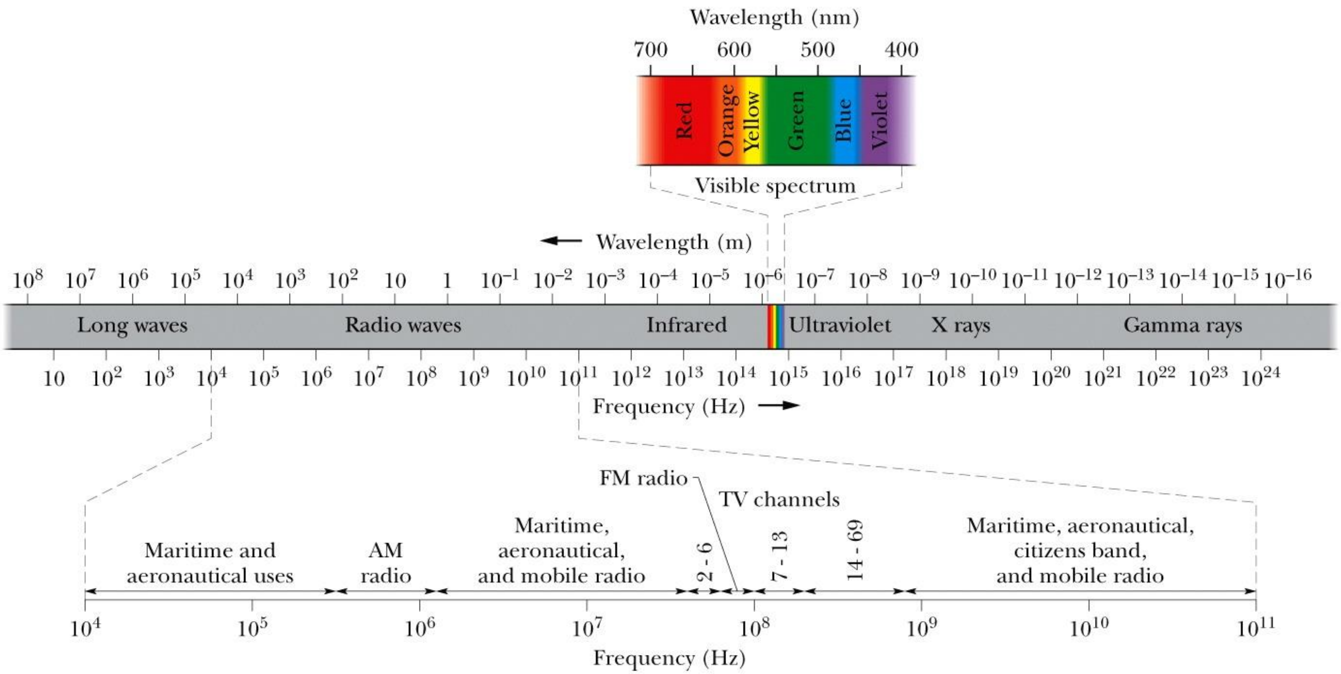
Chapter 33

Electromagnetic Waves

33-1 Electromagnetic Waves

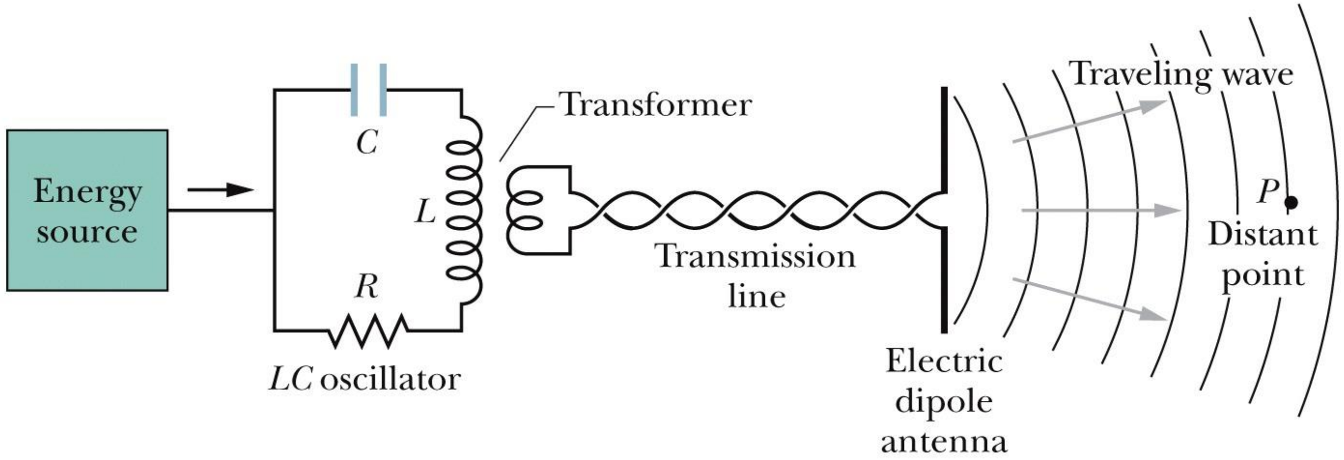
Maxwell's Rainbow



In Maxwell's time (the mid 1800s), the visible, infrared, and ultraviolet forms of light were the only electromagnetic waves known. Spurred on by Maxwell's work, however, Heinrich Hertz discovered what we now call radio waves and verified that they move through the laboratory at the same speed as visible light, indicating that they have the same basic nature as visible light. As the figure shows, we now know a wide spectrum (or range) of electromagnetic waves: Maxwell's rainbow.

33-1 Electromagnetic Waves

Travelling Electromagnetic Wave



An arrangement for generating a traveling electromagnetic wave in the shortwave radio region of the spectrum: an LC oscillator produces a sinusoidal current in the antenna, which generates the wave. P is a distant point at which a detector can monitor the wave traveling past it.

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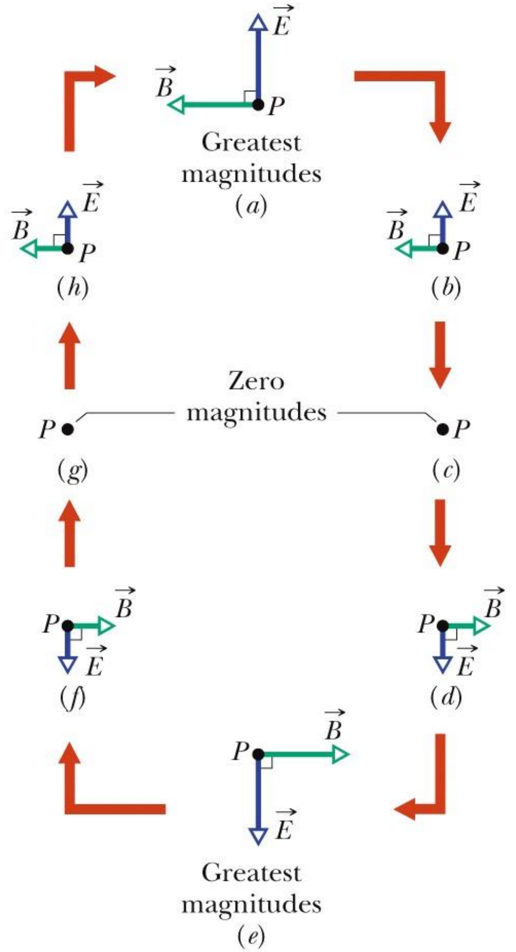
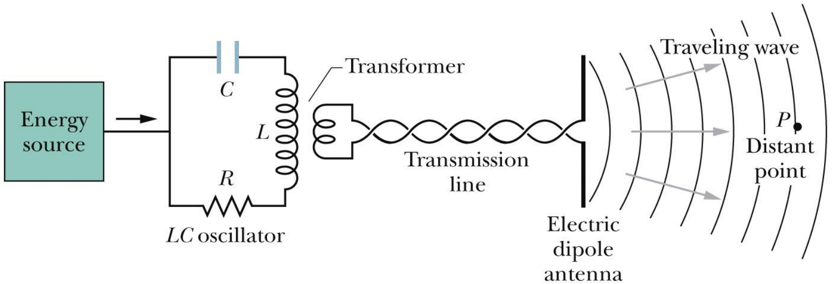


Figure 1

Figure 2



Electromagnetic Wave. Figure 1 shows how the electric field ***E*** and the magnetic field ***B*** change with time as one wavelength of the wave sweeps past the distant point P of Fig. 2 ; in each part of Fig. 1, the wave is traveling directly out of the page. (We choose a distant point so that the curvature of the waves suggested in Fig. 2 is small enough to neglect. At such points, the wave is said to be a plane wave, and discussion of the wave is much simplified.) Note several key features in Fig. 2; they are present regardless of how the wave is created:

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Travelling Electromagnetic Wave

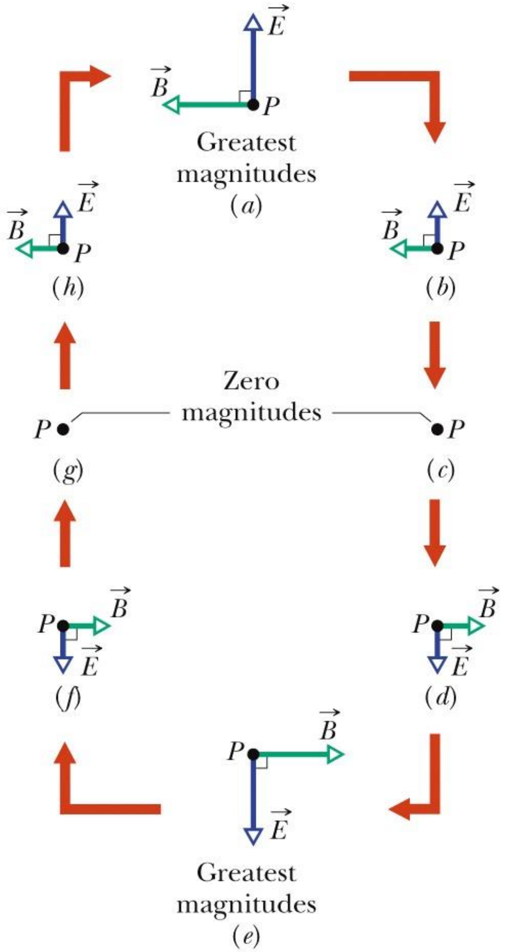
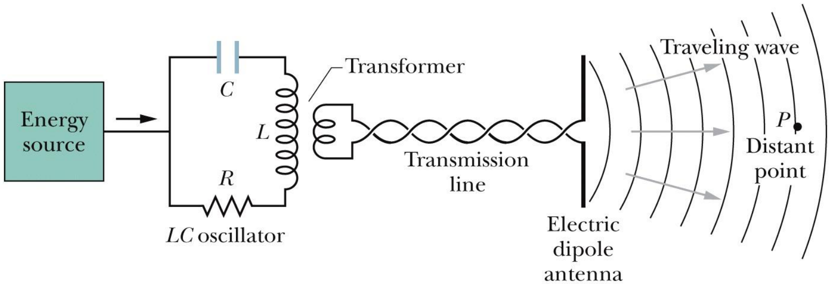


Figure 1

Figure 2



1. The electric and magnetic fields ***E*** and ***B*** are always perpendicular to the direction in which the wave is traveling. Thus, the wave is a transverse wave, as discussed in Chapter 16.
2. The electric field is always perpendicular to the magnetic field.
3. The cross product ***E*** × ***B*** always gives the direction in which the wave travels.
4. The fields always vary sinusoidally, just like the transverse waves discussed in Chapter 16. Moreover, the fields vary with the same frequency and in phase (in step) with each other.

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Travelling Electromagnetic Wave

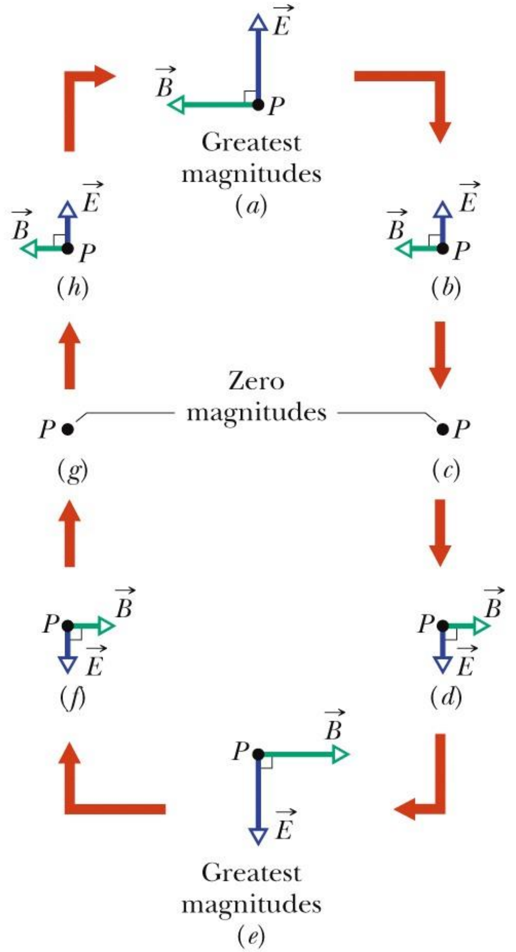
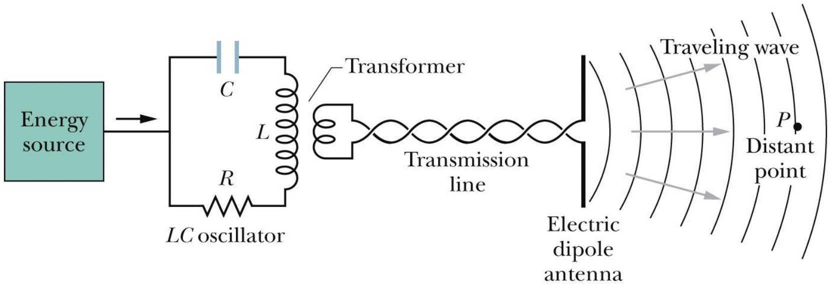


Figure 1

Figure 2



In keeping with these features, we can deduce that an electromagnetic wave traveling along an x axis has an electric field $\boldsymbol{E}$ and a magnetic field $\boldsymbol{B}$ with magnitudes that depend on x and t:

$$E = E_m \sin(kx - \omega t),$$

$$B = B_m \sin(kx - \omega t),$$

where E_m and B_m are the amplitudes of $\boldsymbol{E}$ and $\boldsymbol{B}$. The electric field induces the magnetic field and vice versa.

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Travelling Electromagnetic Wave

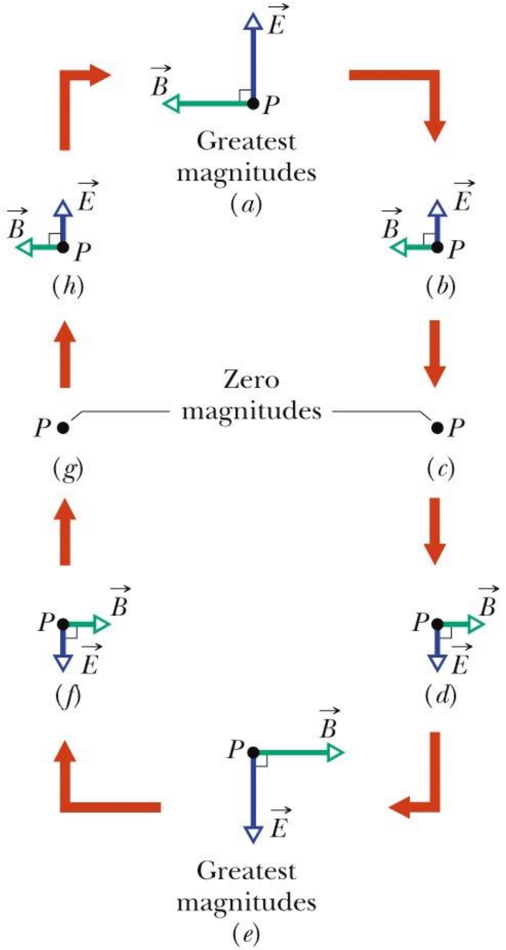
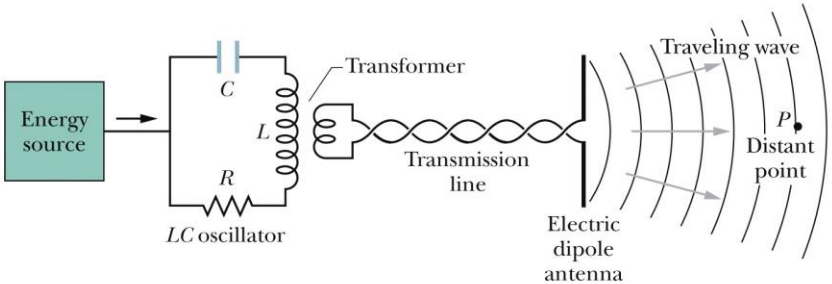


Figure 1

Figure 2



Wave Speed. From chapter 16 (Eq. 16-13), we know that the speed of the wave is *ω/k*. However, because this is an electromagnetic wave, its speed (in vacuum) is given the symbol *c* rather than *v* and that c has the value given by

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} \quad \text{(wave speed)},$$

which is about 3.0×10^8 m/s. In other words,

All electromagnetic waves, including visible light, have the same speed *c* in vacuum.

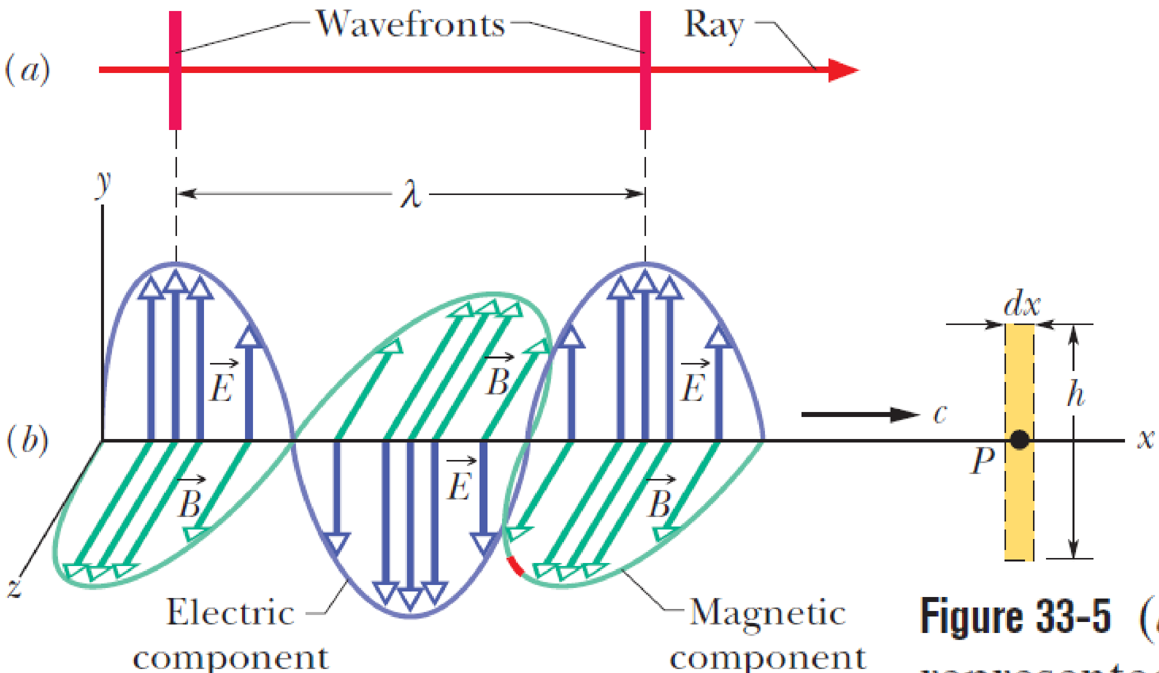
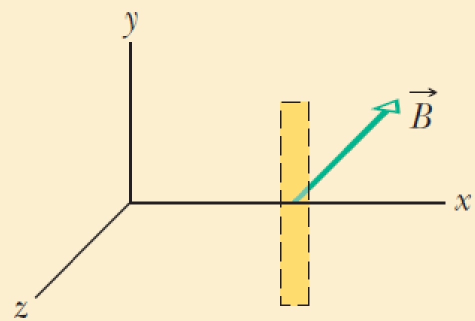


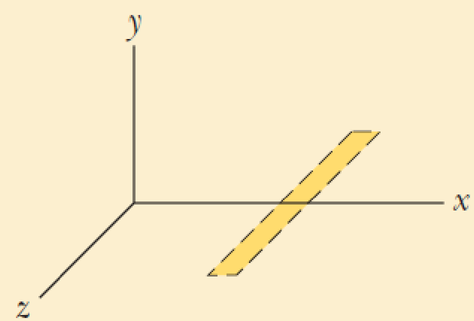
Figure 33-5 (*a*) An electromagnetic wave represented with a ray and two wavefronts; the wavefronts are separated by one wavelength λ. (*b*) The same wave represented in a "snapshot" of its electric field $\vec{E}$ and magnetic field $\vec{B}$ at points on the x axis, along which the wave travels at speed c. As it travels past point P, the fields vary as shown in Fig. 33-4. The electric component of the wave consists of only the electric fields; the magnetic component consists of only the magnetic fields. The dashed rectangle at P is used in Fig. 33-6.

Checkpoint 1

The magnetic field $\vec{B}$ through the rectangle of Fig. 33-6 is shown at a different instant in part 1 of the figure here; $\vec{B}$ is directed in the xz plane, parallel to the z axis, and its magnitude is increasing. (a) Complete part 1 by drawing the induced electric fields, indicating both directions and relative magnitudes (as in Fig. 33-6). (b) For the same instant, complete part 2 of the figure by drawing the electric field of the electromagnetic wave. Also draw the induced magnetic fields, indicating both directions and relative magnitudes (as in Fig. 33-7).



(1)



(2)

CP **1.** (a) (Use Fig. 33-5.) On right side of rectangle, $\vec{E}$ is in negative y direction; on left side, $\vec{E} + d\vec{E}$ is greater and in same direction; (b) $\vec{E}$ is downward. On right side, $\vec{B}$ is in negative z direction; on left side, $\vec{B} + d\vec{B}$ is greater and in same direction.

33-2 Energy Transport and The Poynting Vector

The Poynting Vector: The rate per unit area at which energy is transported via an electromagnetic wave is given by the Poynting vector

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B}$$

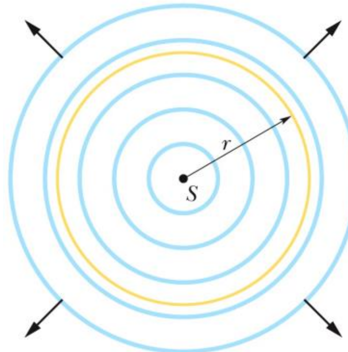
The direction of the Poynting vector $\vec{S}$ of an electromagnetic wave at any point gives the wave's direction of travel and the direction of energy transport at that point.

The time-averaged rate per unit area at which energy is transported is S_{avg}, which is called the intensity I of the wave:

$$I = \frac{1}{c\mu_0} E_{\mathrm{rms}}^2.$$

in which $E_{rms} = E_m/\sqrt{2}$.

The energy emitted by light source S must pass through the sphere of radius r.

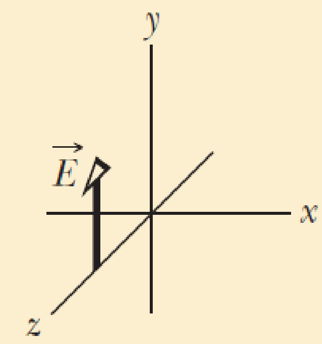


A point source of electromagnetic waves emits the waves isotropically—that is, with equal intensity in all directions. The intensity of the waves at distance r from a point source of power P_s is

$$I = \frac{\text{power}}{\text{area}} = \frac{P_s}{4\pi r^2},$$

Checkpoint 2

The figure here gives the electric field of an electromagnetic wave at a certain point and a certain instant. The wave is transporting energy in the negative z direction. What is the direction of the magnetic field of the wave at that point and instant?



positive direction of x

Sample Problem 33.01 Light wave: rms values of the electric and magnetic fields

When you look at the North Star (Polaris), you intercept light from a star at a distance of 431 ly and emitting energy at a rate of 2.2×10^3 times that of our Sun ($P_{sun} = 3.90 \times 10^{26}$ W). Neglecting any atmospheric absorption, find the rms values of the electric and magnetic fields when the starlight reaches you.

KEY IDEAS

1. The rms value E_{rms} of the electric field in light is related to the intensity I of the light via Eq. 33-26 ($I = E_{rms}^2/c\mu_0$).
2. Because the source is so far away and emits light with equal intensity in all directions, the intensity I at any distance r from the source is related to the source's power P_s via Eq. 33-27 ($I = P_s/4\pi r^2$).
3. The magnitudes of the electric field and magnetic field of an electromagnetic wave at any instant and at any point in the wave are related by the speed of light c according to Eq. 33-5 ($E/B = c$). Thus, the rms values of those fields are also related by Eq. 33-5.

Electric field: Putting the first two ideas together gives us

$$I = \frac{P_s}{4\pi r^2} = \frac{E_{rms}^2}{c\mu_0}$$

and

$$E_{rms} = \sqrt{\frac{P_s c\mu_0}{4\pi r^2}}.$$

By substituting $P_s = (2.2 \times 10^3)(3.90 \times 10^{26}\ \text{W})$, $r = 431\ \text{ly} = 4.08 \times 10^{18}$ m, and values for the constants, we find

$$E_{rms} = 1.24 \times 10^{-3}\ \text{V/m} \approx 1.2\ \text{mV/m}. \qquad \text{(Answer)}$$

Magnetic field: From Eq. 33-5, we write

$$B_{rms} = \frac{E_{rms}}{c} = \frac{1.24 \times 10^{-3}\ \text{V/m}}{3.00 \times 10^8\ \text{m/s}}$$
$$= 4.1 \times 10^{-12}\ \text{T} = 4.1\ \text{pT}.$$

Cannot compare the fields: Note that E_{rms} (= 1.2 mV/m) is small as judged by ordinary laboratory standards, but B_{rms} (= 4.1 pT) is quite small. This difference helps to explain why most instruments used for the detection and measurement of electromagnetic waves are designed to respond to the electric component. It is wrong, however, to say that the electric component of an electromagnetic wave is "stronger" than the magnetic component. You cannot compare quantities that are measured in different units. However, these electric and magnetic components are on an equal basis because their average energies, which *can* be compared, are equal.