36. (a) Eq. 37-36 leads to a speed of

$$v = \frac{\Delta\lambda}{\lambda} c = (0.004)(3.0\times10^{8}\,\text{m/s}) = 1.2\times10^{6}\ \text{m/s} \approx 1\times10^{6}\ \text{m/s}.$$

(b) The galaxy is receding.

37. We obtain

$$v = \frac{\Delta\lambda}{\lambda} c = \left(\frac{620\ \text{nm} - 540\ \text{nm}}{620\ \text{nm}}\right) c = 0.13c.$$

43. (a) The work-kinetic energy theorem applies as well to relativistic physics as to Newtonian; the only difference is the specific formula for kinetic energy. Thus, we use $W = \Delta K$ where $K = m_e c^2(\gamma - 1)$ (Eq. 37-52), and $m_e c^2 = 511$ keV = 0.511 MeV (Table 37-3). Noting that

$$\Delta K = m_e c^2(\gamma_f - \gamma_i),$$

we obtain

$$W = \Delta K = m_e c^2 \left(\frac{1}{\sqrt{1-\beta_f^2}} - \frac{1}{\sqrt{1-\beta_i^2}}\right) = (511\text{keV})\left(\frac{1}{\sqrt{1-(0.19)^2}} - \frac{1}{\sqrt{1-(0.18)^2}}\right)$$

$$= 0.996\ \text{keV} \approx 1.0\ \text{keV}.$$

(b) Similarly,

$$W = (511\text{keV})\left(\frac{1}{\sqrt{1-(0.99)^2}} - \frac{1}{\sqrt{1-(0.98)^2}}\right) = 1055\,\text{keV} \approx 1.1\ \text{MeV}.$$

We see the dramatic increase in difficulty in trying to accelerate a particle when its initial speed is very close to the speed of light.

45. The distance traveled by the pion in the frame of Earth is (using Eq. 37-12) $d = v\Delta t$. The proper lifetime Δt_0 is related to Δt by the time-dilation formula: $\Delta t = \gamma\Delta t_0$. To use this equation, we must first find the Lorentz factor γ (using Eq. 37-48). Since the total energy of the pion is given by $E = 1.35 \times 10^5$ MeV and its mc^2 value is 139.6 MeV, then

$$\gamma = \frac{E}{mc^2} = \frac{1.35\times10^{5}\ \text{MeV}}{139.6\,\text{MeV}} = 967.05.$$

Therefore, the lifetime of the moving pion as measured by Earth observers is

$$\Delta t = \gamma \Delta t_0 = (967.1)(35.0 \times 10^{-9}\ \text{s}) = 3.385 \times 10^{-5}\ \text{s},$$

and the distance it travels is

$$d \approx c\Delta t = (2.998 \times 10^8\ \text{m/s})(3.385 \times 10^{-5}\ \text{s}) = 1.015 \times 10^4\ \text{m} = 10.15\,\text{km}$$

where we have approximated its speed as c (note: its speed can be found by solving Eq. 37-8, which gives v = 0.9999995c; this more precise value for v would not significantly alter our final result). Thus, the altitude at which the pion decays is 120 km – 10.15 km = 110 km.

48. (a) The proper lifetime Δt_0 is 2.20 μs, and the lifetime measured by clocks in the laboratory (through which the muon is moving at high speed) is Δt = 6.90 μs. We use Eq. 37-7 to solve for the speed parameter:

$$\beta = \sqrt{1 - \left(\frac{\Delta t_0}{\Delta t}\right)^2} = \sqrt{1 - \left(\frac{2.20\ \mu\text{s}}{6.90\ \mu\text{s}}\right)^2} = 0.948\,.$$

(b) From the answer to part (a), we find γ = 3.136. Thus, with (see Table 37-3)

$$m_\mu c^2 = 207 m_e c^2 = 105.8\ \text{MeV},$$

Eq. 37-52 yields

$$K = m_\mu c^2 (\gamma - 1) = (105.8\,\text{MeV})(3.136 - 1) = 226\,\text{MeV}.$$

(c) We write $m_\mu c$ = 105.8 MeV/c and apply Eq. 37-41:

$$p = \gamma m_\mu v = \gamma m_\mu c\beta = (3.136)(105.8\,\text{MeV}/c)(0.9478) = 314\ \text{MeV}/c$$

which can also be expressed in SI units ($p = 1.7 \times 10^{-19}$ kg·m/s).

33-24. We require $F_{\text{grav}} = F_r$ or

$$G\frac{mM_s}{d_{es}^2} = \frac{2IA}{c},$$

and solve for the area A:

$$A = \frac{cGmM_s}{2Id_{es}^2} = \frac{(6.67 \times 10^{-11}\ \text{N} \cdot \text{m}^2/\text{kg}^2)(1500\ \text{kg})(1.99 \times 10^{30}\ \text{kg})(2.998 \times 10^8\ \text{m/s})}{2(1.40 \times 10^3\ \text{W/m}^2)(1.50 \times 10^{11}\ \text{m})^2}$$

$$= 9.5 \times 10^5\ \text{m}^2 = 0.95\ \text{km}^2.$$

33-29. If the beam carries energy *U* away from the spaceship, then it also carries momentum *p* = *U*/*c* away. Since the total momentum of the spaceship and light is conserved, this is the magnitude of the momentum acquired by the spaceship. If *P* is the power of the laser, then the energy carried away in time *t* is *U* = *Pt*. We note that there are 86400 seconds in a day. Thus, *p* = *Pt*/*c* and, if *m* is mass of the spaceship, its speed is

$$v = \frac{p}{m} = \frac{Pt}{mc} = \frac{(10 \times 10^3\ \text{W})(86400\ \text{s})}{(1.5 \times 10^3\ \text{kg})(2.998 \times 10^8\ \text{m/s})} = 1.9 \times 10^{-3}\ \text{m/s}.$$