SOLUTION The period of the Earth is $T_E = 1\text{ yr}$, and the distance of Earth from the Sun is $r_{ES} = 1.50 \times 10^{11}\text{ m}$. From Kepler's third law (Eq. 5–6b):

$$\frac{r_{MS}}{r_{ES}} = \left(\frac{T_M}{T_E}\right)^{\frac{2}{3}} = \left(\frac{1.88\text{ yr}}{1\text{ yr}}\right)^{\frac{2}{3}} = 1.52.$$

So Mars is 1.52 times the Earth's distance from the Sun, or 2.28×10^{11} m.

EXAMPLE 5–16 **The Sun's mass determined.** Determine the mass of the Sun given the Earth's distance from the Sun as $r_{ES} = 1.5 \times 10^{11}\text{ m}$.

PHYSICS APPLIED

Determining the Sun's mass

APPROACH Equation 5–6a relates the mass of the Sun M_S to the period and distance of any planet. We use the Earth.

SOLUTION The Earth's period is $T_E = 1\text{ yr} = \left(365\tfrac{1}{4}\text{d}\right)(24\text{ h/d})(3600\text{ s/h}) = 3.16 \times 10^7\text{ s}$. We solve Eq. 5–6a for M_S:

$$M_S = \frac{4\pi^2 r_{ES}^3}{GT_E^2} = \frac{4\pi^2\left(1.5 \times 10^{11}\text{ m}\right)^3}{\left(6.67 \times 10^{-11}\text{ N}\cdot\text{m}^2/\text{kg}^2\right)\left(3.16 \times 10^7\text{ s}\right)^2} = 2.0 \times 10^{30}\text{ kg}.$$

Accurate measurements on the orbits of the planets indicated that they did not precisely follow Kepler's laws. For example, slight deviations from perfectly elliptical orbits were observed. Newton was aware that this was to be expected because any planet would be attracted gravitationally not only by the Sun but also (to a much lesser extent) by the other planets. Such deviations, or **perturbations**, in the orbit of Saturn were a hint that helped Newton formulate the law of universal gravitation, that all objects attract gravitationally. Observation of other perturbations later led to the discovery of Neptune and Pluto. Deviations in the orbit of Uranus, for example, could not all be accounted for by perturbations due to the other known planets. Careful calculation in the nineteenth century indicated that these deviations could be accounted for if another planet existed farther out in the solar system. The position of this planet was predicted from the deviations in the orbit of Uranus, and telescopes focused on that region of the sky quickly found it; the new planet was called Neptune. Similar but much smaller perturbations of Neptune's orbit led to the discovery of Pluto in 1930.

Perturbations and discovery of planets

Starting in the mid–1990s, planets revolving about distant stars (Fig. 5–30) were inferred from the regular "wobble" of each star due to the gravitational attraction of the revolving planet(s).

Planets around other stars

The development by Newton of the law of universal gravitation and the three laws of motion was a major intellectual achievement: with these laws, he was able to describe the motion of objects on Earth and in the heavens. The motions of heavenly bodies and objects on Earth were seen to follow the same laws. For this reason, and also because Newton integrated the results of earlier scientists into his system, we sometimes speak of *Newton's synthesis*.

Newton's synthesis

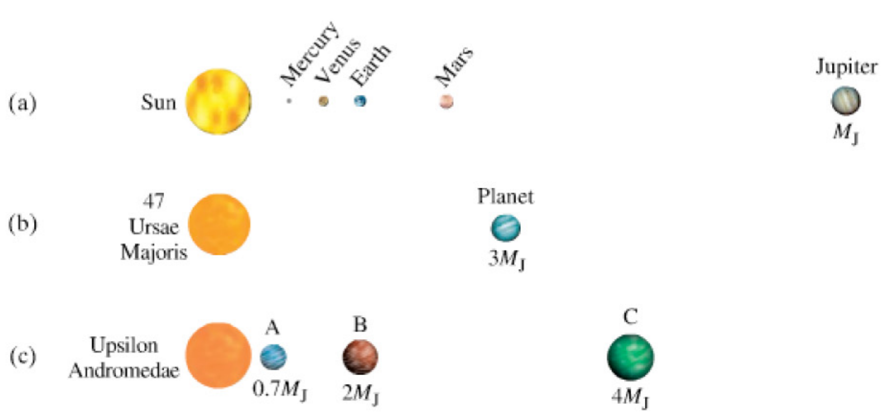

FIGURE 5–30 Our solar system (a) is compared to recently discovered planets orbiting (b) the star 47 Ursae Majoris and (c) the star Upsilon Andromedae with at least three planets. M_J is the mass of Jupiter. (Sizes not to scale.)