12.4 ▪ PROPERTIES OF EXOPLANETS

Recent searches for exoplanets have contributed greatly to our knowledge of planetary properties. First, and most fundamental, these searches have shown that exoplanets exist, and that the Sun is not unique in having an entourage of planets. By the middle of the year 2008, about 300 exoplanets had been discovered, primarily by the radial velocity and transit methods. With such large numbers of planets known, it becomes useful to do statistical analysis of planetary properties. When doing the statistics, however, we must keep in mind the selection biases involved in searches for exoplanets. The radial velocity method favors the discovery of high-mass planets on small orbits; the transit method favors the discovery of large-radius planets on small orbits. In general, big things are easier to detect than small things; it's easier to detect a hippopotamus in your living room than it is to detect an ant. Despite the ease of detection, it is still surprising, however, to find a hippo lounging on your sofa.

One of the most startling results of exoplanet searches is the astronomical equivalent of finding a living-room hippo; searches have revealed a significant population of **hot Jupiters**, where a hot Jupiter is a planet with a mass comparable to that of Jupiter, on an orbit with $a \lesssim 0.1$ AU.[4] It is estimated that $\sim 1\%$ of stars surveyed have planets with $M_{\rm B} \sin i \geq 0.5 M_{\rm Jup}$ on orbits with $a \leq 0.1$ AU. Going out to larger radii, $\sim 6\%$ of the stars have planets in the same mass range on orbits with $a \leq 5$ AU, comparable to the size of Jupiter's orbit.

Figure 12.9a shows $M_{\rm B} \sin i$ as a function of semimajor axis length a for exoplanets detected with the radial velocity technique. Exoplanets lying below the dashed line in the figure would produce a radial velocity of $v_r \lesssim 3\ {\rm m\ s^{-1}}$ in their parent star, and thus would be difficult to detect using current techniques. In addition, exoplanets with $a \gtrsim 5$ AU would have orbital periods of $P \gtrsim 11$ yr, assuming a $1 M_\odot$ parent star; few stars have been monitored for a long enough time at high enough spectral resolution to detect such long-period planets. Of the eight major planets in our solar system, indicated as the squares in Figure 12.9, only Jupiter falls within the region of parameter space where exoplanets can be reliably detected. Thus, current techniques for finding exoplanets cannot tell us about Earth-mass planets on Earth-like orbits. They are most effective at finding types of planets that are *not* seen in our own solar system: "hot Jupiters" and "hot Neptunes."

In the previous section, we discussed, for the sake of simplicity, the case of exoplanets on nearly circular orbits. If an exoplanet is on a circular orbit with constant orbital speed, then the radial velocity variations of its parent star will trace out a sinusoidal curve. If the star's radial velocity variations are not sinusoidal, that is a sign that the perturbing exoplanet is on an eccentric orbit with varying orbital speed. If the shape of the radial velocity curve is measured with sufficient accuracy, the eccentricity of the exoplanet's orbit can be calculated. Figure 12.9b shows the orbital eccentricity e as a function of semimajor axis length a for exoplanets detected with the radial velocity method. Exoplanets on extremely small orbits ($a \lesssim 0.05$ AU) tend to have nearly circular orbits; this is a result of the very strong tides acting on these planets. At larger radii, however,

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[4] For comparison, Mercury has $a \approx 0.4$ AU and $M \approx 0.0002 M_{\rm Jup}$.

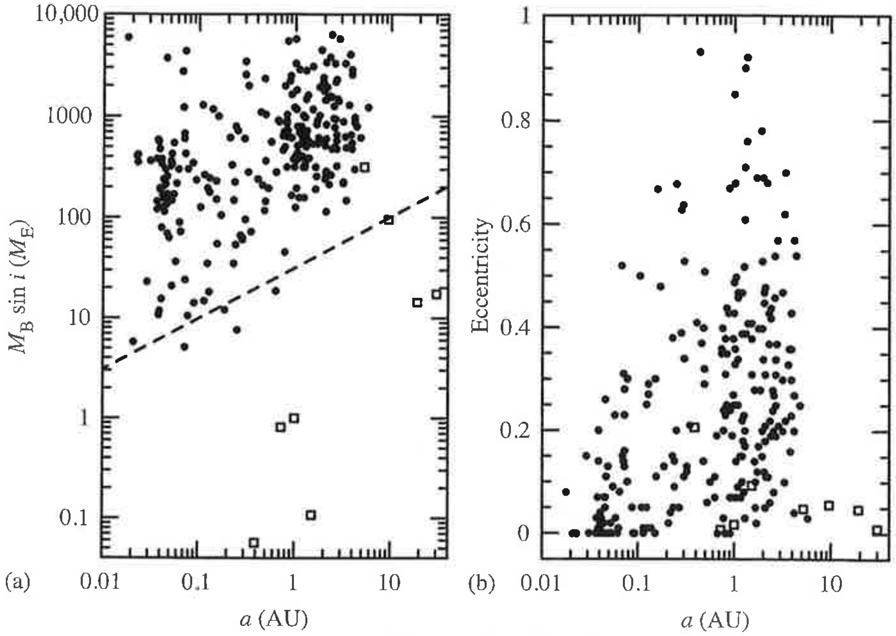

FIGURE 12.9 (a) $M_B \sin i$ as a function of orbit size a for planets detected by the radial velocity technique. The dashed line is the value of $M_B \sin i$ that would produce $v_r \approx 3$ m s^{-1} in a Sun-like star. (b) Eccentricity e as a function of orbit size a. In both (a) and (b), solar system planets are indicated by squares.

exoplanets have a wide range of eccentricities. This is a strong contrast to the eccentricity of planetary orbits within the solar system (shown as the squares in Figure 12.9b).

The search for exoplanets has thus provided some surprising results. The discovery of hot Jupiters posed a challenge to existing models for the formation and evolution of planetary systems. Jovian planets should not be able to form within 0.1 AU of a Sun-like star; the temperature there is too hot for even the most refractory substances to condense into solids. Thus, hot Jupiters must be formed far from their parent stars, then migrate inward. To move from a large orbit to a smaller one, a planet must lose orbital angular momentum. There are various mechanisms by which a young planet can lose angular momentum. Planets initially form in gaseous protoplanetary disks (see Figure 8.3). The viscous gas of the disk can exert a torque on protoplanets as they form, decreasing their orbital angular momentum and driving them to smaller orbits. At a later stage, close encounters with planetesimals can transfer angular momentum from the exoplanet to the planetesimals. Finally, if two planets have a close encounter (as opposed to a collision, like the one that formed the Moon), orbital angular momentum will be transferred from one planet to the other. In this case, one planet will be driven inward to a smaller orbit, while the other will be driven outward (and may even attain escape speed). It is not yet known which of these mechanisms is the primary one that drives hot Jupiters inward.