Extrasolar Planets

On October 6, 1995, Swiss astronomers, Michele Mayor and Didier Queloz of the Geneva Observatory (Nature **378**, 355(1995)) announced that they had discovered a planet around the star 51 Pegasi (51 Peg A). They studied this star for about 18 months, using a precise spectroscope mounted on a 1.9-meter telescope at the Observatorie de Haute-Provence in France. The detection was accomplished by the radial velocity technique.

According to the nonrelativistic Doppler formula, $\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$, the shift in the line position in a star's spectrum, $\Delta\lambda = \lambda - \lambda_0$, can be directly translated to a radial velocity for the motion of star. For most of the star's orbit, the motion of the star will not be along the line of sight, but when the spectral line shift reaches its maximum, the star is either moving directly toward us or away from us, thus defining an orbital velocity for the star.

Mayor and Queloz found a maximum radial velocity of 59 m/sec, see Fig. 1. From the velocity curve, they discerned two important orbital parameters. By monitoring two maxima, they determined an orbital period for the star, $\tau = 4.23$ days, and an orbital eccentricity of nearly zero, $\epsilon \sim 0$. We know that when the velocity curve exhibits purely sinusoidal motion, the orbit is circular.

FIGURES

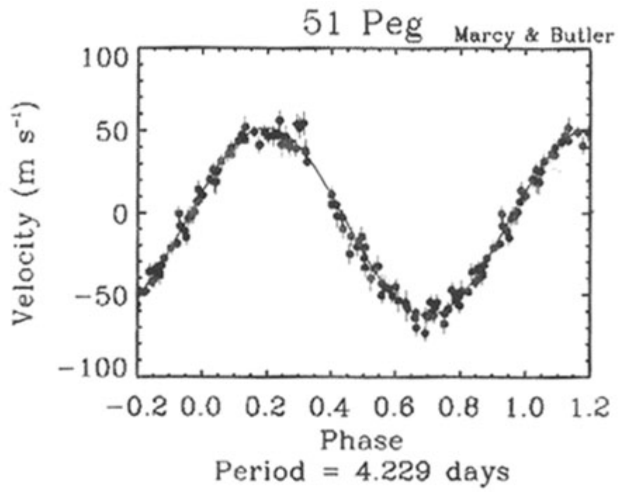

FIG. 1.

When we speak of the orbital motion of a star, we refer to the motion of the star relative to another neighboring object(s). For this particular star, the neighboring binary companion turns out to be a planet! Nevertheless, the signature of the motion of the planet on 51 Peg A is manifest as a stellar radial velocity of 59 m/sec. Because the star-planet system is revolving around its center of mass (barycenter), the period of the star's orbit equals that of the orbital period of the planet.

Kepler's third law states that for a binary system, the size of the orbit is proportional to its period according to

$$a^3 = \frac{G}{4\pi^2}(M_p + M_s)\tau^2 \qquad (1)$$

where M_p and M_s are, respectively, the masses for the planet and the star. Since the assumption is that $M_s >> M_p$, and only one component of the binary system is revealed in the radial velocity measurement, we need to replace the total mass in the above equation. Realizing that the star velocity is given as $K_s = \frac{2\pi}{\tau}a$, and rearranging terms, we obtain

$$\frac{K_s \tau}{2\pi G} = (M_s + M_p) \qquad (2)$$

We also know that $M_s + M_p = \frac{\tau}{2\pi G}\frac{1}{\sin i^3}(K_s + K_p)^3$. Because $\frac{M_p}{M_s} = \frac{K_s}{K_p}$, we can substitute for K_p everywhere to get

$$M_s + M_p = \frac{\tau}{2\pi G}\frac{1}{\sin i^3}(1 + \frac{M_s}{M_p})^3 K_s^3 \tag{3}$$

So that,

$$f(M) = \frac{(M_p \sin i)^3}{(M_s + M_p)^2} = \frac{\tau}{2\pi G}K_s^3 \tag{4}$$

The l.h.s of this equation is know as the mass function. Since we know K_s and τ, the mass function for 51 Peg A is determined to be

$$f(M) = 1.36 \times 10^{20}\text{kg} \tag{5}$$

51 Peg A is a type-G star, much like our Sun, with a mass of about $M_s = 0.95M_\odot$ and a surface temperature of about 5700 K. Assuming that $M_p << M_s$, gives

$$M_p \sin i = [1.36 \times 10^{20} M_s^2]^{1/3} \tag{6}$$

Since $M_\odot = 2 \times 10^{30}$ kg, $M_s = 8 \times 10^{26}$ kg $= 0.45 M_J$.

Therefore, 51 Peg B, as the planet is known, appears to be a gas giant planet. Note that in the above calculation, it is assumed that the orbital plane of the star-planet system is "edge-on", i. e. $i = 90°$. This, of course, puts a lower limit on the mass of the planet, because $0 \leq \sin i \leq 1$. If, for instance, the angle of inclination of the orbit is $i \sim 3°$, then $M_p \sim 9M_J$, which brings up an interesting puzzle: is 51 Peg B really a giant planet or a very small star? It has been speculated that this planet is a brown dwarf (BD). BDs are small faint objects whose mass does not exceed $0.05M_\odot$ (see next chapter) and hence are not sufficiently massive to ignite the nuclear fusion process.

One can also calculate the orbital radius of 51 Peg B as $a = \frac{K_s \tau}{2\pi} \sim 3000$ km, and from $\frac{M_s}{M_p} = \frac{a_p}{a}$, $a_p = 7.1 \times 10^6$ km =0.05 AU.

Compare the orbital parameters for 51 Peg B to the closest planet to the sun. Mercury has a mass of about $M_m \sim 0.0002 M_J$ at a mean distance of $a_m = 0.387$ AU in an orbit with $\epsilon_m = 0.206$. It is in fact the closeness of 51 Peg B to the parent star that allowed for its observation through the reflex motion.

Practically, all of the observed extrasolar planets to date, there are about 28, have been detected by the radial velocity technique, as outlined above. A large majority of these planets have large eccentric orbits, $0.0 \leq \epsilon < 0.7$ and masses in the range of $0.5 M_J < M_p < 5 M_J$. It is understood that the observed masses by the radial velocity techniques constitute lower limits on the actual masses.

A recent photometric technique has been able to observe the transit of a planet across the star HD209458. This technique which measures that dimming of star light as the companion planet crosses the surface of the star, much like a solar eclipse, allows observers to determine the true mass of the planet and also its size. In an accurate measurement of the photometric dimming of HD209458 by the passage of a planet across the stellar disk on September 9 and 16, 1999, the observers (ApJ Lett. **529**, L45 (2000)), were able to determine the true mass of the planet to be $M_p = 0.63 M_J$ and its radius to be $R_p = 1.27 R_J$, knowing the radial velocity for the star, K_s, the mass of the star, $M_s = 1.1 M_\odot$, and the orbital period, $\tau = 3.525$ days. From the Kepler's law, one obtains a value for the star's semimajor axis to be $a = 0.0467$ AU.

The relative flux as a function of time for the eclipse of HD209458 is shown in Fig. 2. The dots represent the measurements of the flux on September 9 and 16, 1999. The solid line results from a best fit to data, giving an angle of inclination of $i = 87.1°$, implying that the orbit of the planet is edge-on to the line of sight. The two dashed lines represent fits to data assuming a planet 10% larger and smaller in radius. Because the size and the mass of the planet were determined, other physically important parameters could be calculated for the first time. The average density of this planet is found to be $\rho \sim 0.38$ g/cm^3, much less than the density of Jupiter, $\rho_J = 1.31$ g/cm^3. The surface gravity of the planet is $g \sim 970$ cm/sec^2.

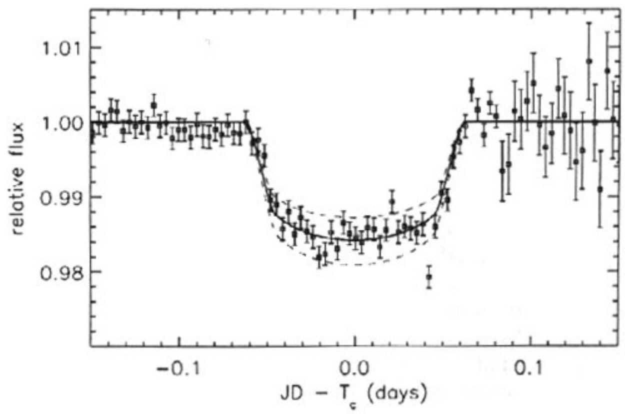

FIG. 2.