LETTER TO THE EDITOR

Based on a presentation made at the 89th Annual Meeting of the AAVSO, October 27, 2000

"Favorable Times Predicted for Searching for Transits of Gliese 876 = IL Aquarii by its Giant Planets"

Gliese 876 = IL Aqr is a red dwarf (M4V spectral type) star 971,000 a. u. (15.4 light years) from the solar system with magnitude $V = 10.16$ and color indices $(B\text{-}V) = 1.58$, $(R\text{-}I) = 1.22$. It is in Aquarius, with equatorial coordinates $\alpha\,(2000) = 22^{h}\,53^{m}\,20^{s}$, $\delta\,(2000) = -14°\ 13.2'$, ecliptic coordinates $\lambda\,(2000) = 339.20°$, $\beta\,(2000) = -06.59°$, and galactic coordinates $l = 52.01°$, $b = -59.62°$. Marcy *et al.* (G. W. Marcy *et al.*, 1998, *Astrophys. J. L.*, **505**, L147), who have recently discovered two giant planets orbiting Gliese 876, estimated its luminosity $L = 0.0124L_{\odot}$, its mass $M = 0.32M_{\odot}$, and its radius as $R \approx 170{,}000$ km. E.Weis (1994, *Astron. J.*, **107**, 1135) found Gliese 876 to have slight variability (amplitude ≈ 0.04 magnitude) with possible periods of 20.2 and 28.7 days; it now has the name IL Aquarii (E. V. Kazarovets and N. N. Samus, 1997, *IBVS*, No. 4471).

Marcy *et al.* (1998) found a small periodic radial velocity variation with amplitude K for Gliese 876 caused by a planet or planets orbiting it (Gliese 876b). Delfosse *et al.* (X. Delfosse, *et al.*, 1998, *AstronAstrophys.L.*, **338**, L67) independently discovered this variation and found the center of mass of Gliese 876 and its planets to have the radial velocity $\gamma = -1.9$ km/s. The proper motion of Gliese 876 is 1".1692 + 0".003/year, so that it has the space velocity 26.16 km/s relative to the Sun. These teams initially thought that one planet produces the variation, but recently (R. Cowen, 2001, *Science News*, **159**, No. 2, 22) reported that Marcy's team has found evidence for a second planet (Gliese 876c) orbiting closer to the star than the first-detected, more massive planet (Gliese 876b). Later, A. MacRobert (2001, *Sky & Telescope*, **101**, No. 4, 20) discussed this planetary system in more detail and gave minimum masses of $1.9M_J$ for Gliese 876b, and $0.6M_J$ for Gliese 876c, where M_J is Jupiter's mass. The information in Marcy *et al.* (1998), Cowen (2001), and MacRobert (2001) enable the following orbital elements to be found for the perturbation of Gliese 876b:

Period $P_b = 61.0 \pm 0.15$ days
Orbital Eccentricity $e_b = 0.07 \pm 0.05$
Longitude of Periastron $\omega_b = 24° \pm 6°$
Periastron Date $T_b = 2450301.0 \pm 1.0$ JD
Semi-major Axis $a_b = 0.21$ a.u.
Radial Velocity Amplitude $K_b = 211 \pm 5$ m/s ;

and for the perturbation by Gliese 876c:

$P_c = 30.1 \pm 0.2$ days
$e_c = 0.3 \pm 0.05$
$\omega_c = 48° \pm 6°$
$T_c = 2450303.1 \pm 1.0$ JD
$a_c = 0.13$ a. u.
$K_c = 87 \pm 5$ m/s .

The orbital elements ω_b, T_b, and a_b are taken from Marcy *et al.* (1998); elements P_b and P_c are taken from MacRobert (2001); e_b, e_c, and ω_c are derived from information in Cowen (2001); and the remaining elements are derived from the equations for the two-body problem in T. E. Sterne (1960, *An Introduction to Celestial Mechanics*, Interscience, New York, pp. 8–14). The radii R_b and R_c estimated for Gliese 876b and Gliese 876c are $R_b \approx R_c \approx 70{,}000$ km, close to Jupiter's mean radius. This estimate is based on models computed by Burrows *et al.* (A. Burrows *et al.*, 1997, *Planets Beyond the Solar System and the Next Generation of Space Missions*, D. R. Soderblom,ed., Astron. Soc. Pacific Conf. Series, Vol. 119, pp 9–17) that had radii within 10% of Jupiter's over a wide range of giant planet and brown dwarf masses. Equation (2) in F. R. West (1996, *J. Amer. Assoc. Var. Star Obs.*, **24**, 19) predicts that a planet of this radius will change the magnitude of Gliese 876 by 0.20 magnitude during a full transit.

A transit of Gliese 876 by its planets can occur when

$$(w + \omega) = 90°, \tag{1}$$

where w is the true anomaly of a planet in its orbit. For the values of ω shown above, $w_b = 66°$ for a transit of Gliese 876 by Gliese 876b, and $w_c = 42°$ for a transit by Gliese 876c. The other orbital elements for Gliese 876 used with the equations for the two-body problem in Sterne (1960) predict that any transits of it might occur 9.97 days after periastron for Gliese 876b, when the star-planet distance would be 0.2032 a.u. (30,400,000 km), and the planet's tangential velocity relative to Gliese 876 would be $V_T = 37.7$ km/s. Future times of transit t_{trb} may be predicted from the equation

$$t_{trb} = T_b + 9.97 + nP_b\ , \tag{2a}$$

where $n = 1, 2, 3,\ldots.$ Substituting the values given above for T_b and P_b and solving, one finds

$$t_{trb} = \text{JD } 2450310.97 + 61n \tag{2b}$$

One finds that Gliese 876c might transit Gliese 876 1.9 days after periastron; thus, by analogy with Equation (2b), one expects any transits by Gliese 876c to occur at the times t_{trc} found from

$$t_{trc} = \text{JD } 2450305.0 + 30.1n' \tag{3}$$

where $n' = 1, 2, 3,\ldots.$ Uncertainties in the orbital elements make the times t_{trb} and t_{trc} uncertain by several days. Therefore, Gliese 876 should be monitored for transits during "opportunity windows" lasting ten days or longer. Six periods of revolution of Gliese 876b equal 366 days, slightly longer than the length of the average Gregorian calendar year (365.2425 days). Thus, opportunity windows will occur on the same days of the calendar year for many years. Gliese 876 rises at sidereal time 1742 and sets at 0404 for an observer at 40° N latitude. Thus, favorable opportunity windows for observing Gliese 876 in the morning before sunrise occur from late May to September, and in the evening sky after sunset from September to late January. Opportunity windows from February to mid-May are unfavorable because the Sun is too close to the direction of Gliese 876.

Times t_{trb} and t_{trc} calculated from Equations (2b) and (3) for $29 \le n \le 32$ and $58 \le n' \le 66$, respectively, are listed in Column 3 in Table 1, the corresponding dates and UTs are shown in Column 4, and the corresponding opportunity windows for observations are shown in Column 5.

The probability P_{tr} that transits occur at all, assuming that planetary orbits have random orientations in space, is, by analogy with Equation (1) in F. R. West (1999, *J. Amer. Assoc. Var. Star Obs.*, **27**, 77),

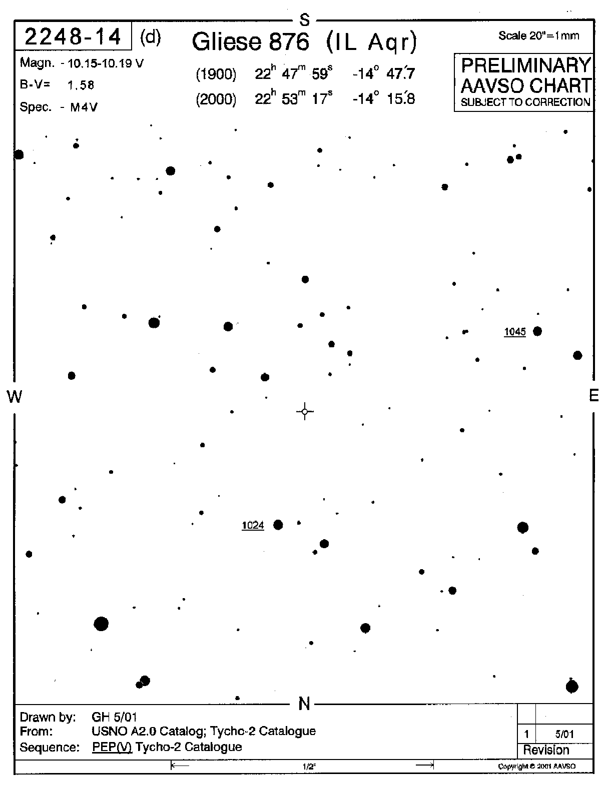
$$P_{tr} = (R/r)\ ; \tag{4}$$

where r is the distance between the star and the planet. From the value of r for Gliese 876b given above for the expected conditions of any transit by it, $P_{tr} = 0.0056$, and the maximum possible duration of a transit is 3.53 hours. Gliese 876c would transit at 14,470,000 km from Gliese 876 with $V_{Tc} = 59.9$ km/s; hence, $P_{trc} = 0.01175$, and a transit could last as long as 2.2 hours. Also, if the planetary orbits are not coplanar (as is

Table 1. Predicted times and "Opportunity Windows" for detecting possible future transits of Gliese 876 by its planets.

n	*n'*	t_{trb} *and* t_{trc} *(JD)*	t_{trb} *and* t_{trc} *(Date and UT)*	*Opportunity Window*
	58	2452050.8	May 21, 2001 0712	May 16–27, 2001
29		2452079.97	June 19, 2001 1117	June 14–26, 2001
	59	2452080.9	June 20, 2001 0936	June 14–26, 2001
	60	2452111.0	July 20, 2001 1200	July 15–26, 2001
30		2452140.97	August 19, 2001 1117	August 14–25, 2001
	61	2452141.1	August 19, 2001 1424	August 14–25, 2001
	62	2452171.2	September 18, 2001 1648	September 13–24, 2001
	63	2452201.3	October 18, 2001 1912	October 13–25, 2001
31		2452201.97	October 19, 2001 1117	October 13–25, 2001
	64	2452231.4	November 17, 2001 2136	November 12–23, 2001
	65	2452261.5	December 18, 2001 0000	December 12–24, 2001
32		2452262.97	December 19, 2001 1117	December 12–24, 2001
	66	2452291.6	January 17, 2002 0224	January 11–23, 2002

true for the solar system), the probability that one transit occurs is 0.0173. Thus, the recent discovery of Gliese 876c significantly increases the probability for transits to occur in this closest verified extrasolar planetary system. If the planets simultaneously transit Gliese 876, the star could be dimmed by as much as 0.45 magnitude.



Gliese 876 should be observed during future opportunity windows for any transits that might occur. Detection of transits would yield valuable information about both Gliese 876, the transiting planet(s), and the planetary system. Very precise magnitudes and times are essential for observations to be meaningful and useful, so only CCD or photoelectric observations should be made; visual observations are not sufficiently precise. Please use the accompanying chart, and report all observations directly to the author.

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