change by about half. A different assumption regarding the vertical profile of induced mean temperature perturbations might have reduced the calculated negative feedback by a factor of 3 or 4. Nevertheless, it is in the right direction to contribute to the explanation of the relatively modest observed global warming.

The apparent consistency between sea level changes and the effective warming may be spurious. Our arguments included gross approximations. A very important link is the change in the volume of the polar ice sheets, for which credible estimates are not now available. It is possible, however, to acquire measurements of the polar ice sheets with sufficient accuracy to confirm their crucial role in global climate change. Satellite-borne radio altimeters, as demonstrated on GEOS-3 and Seasat (*6*), can now measure the surface elevation of ice sheets to within about 2 m. Since the ratio of the area of the West Antarctic ice sheet to that of the ocean is of the order of 1 to 200, a mean change in the thickness of the ice of 2 m corresponds to a sea level change of about 1 cm. Thus satellite altimetry is capable of supplying the important connecting link in an assessment of the relative roles of externally produced heating and ice melting in bringing about observed changes in sea level.

Another geophysical measurement that can contribute to our interpretation of these changes is the rate of rotation of the earth. The discharge and subsequent dispersion as meltwater of large quantities of polar ice is, in effect, a mass transfer away from the earth's axis of rotation and must change the earth's moment of inertia. This change should be reflected in the planet's rate of rotation. The magnitude of this effect can be estimated if one takes the difference in moment of inertia between a uniform layer of water, equivalent to a thin spherical shell, and a polar ice cap composed of the same mass of water circling the globe as an annulus at high latitude (*7*). This difference, divided by the nominal value for the earth's moment of inertia, provides an approximation for the fractional change in the earth's rate of rotation

$$\Delta\dot{m} = \frac{I_s - I_i}{I_e} \qquad (4)$$

where $I_s = 2/3\Delta Mr^2$, $I_i = \Delta M(r\cos\theta)^2$, $I_e = 8.04 \times 10^{37}$ kg-m^2 (the earth's moment of inertia), r is the radius of the earth, and θ is the mean latitude (taken to be 80°S) of the West Antarctic ice sheet, which is assumed to be the principal source of the discharged ice. The calculated value of the relative change in the earth's rate of rotation that one should expect during the last 40 years (during which most of this discharge is presumed to have occurred) is 1.5×10^{-8}. This accounts for about three quarters of the fractional reduction in the earth's angular velocity that has been observed during this period (*8*).

One can conclude from these considerations that global mean sea level, the earth's speed of rotation, and the masses of the polar ice sheets are important parameters for the detection and identification of global climate change. Each factor separately provides extremely important information, but the value of these factors taken together in allowing us to make credible assessments of the interactive behavior of sea level and global mean temperature would be especially great.

For the present it can only be stated as a reasonable hypothesis that the rapid rise in sea level over the past 40 years, and especially since 1970, is due primarily to the accelerated discharge of polar ice sheets. The extraction of latent heat as a consequence of the discharge and melting of more than 50,000 km^3 of ice over the past 40 years has significantly reduced the net sensible increase in global mean surface temperatures.

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Occultation by a Possible Third Satellite of Neptune

Abstract. *The 24 May 1981 close approach of Neptune to an uncataloged star was photoelectrically monitored from two observatories separated by 6 kilometers parallel to the occultation track. An 8.1-second drop in signal, recorded simultaneously at both sites, is interpreted as resulting from the passage of a third satellite of Neptune in front of the star. From the duration of the event, the derived minimum diameter for an object sharing Neptune's motion is 180 kilometers. If the object was in Neptune's equatorial plane and there are no significant errors in the prediction ephemeris, the object was located at a distance of 3 Neptune radii from Neptune's center.*

The occultation of a star by Neptune is an unusual event, occurring about once a year for stars that are sufficiently bright to permit their observation (*1*). Such events provide a unique opportunity to probe the space near Neptune for faint rings and satellites and to investigate the structure of Neptune's upper atmosphere. It was the observation of an occultation of a star by Uranus that revealed that planet's multiple ring system (*2*). Several groups have undertaken programs for observation of occultations by Neptune. Initial reports of three such events mention one partial secondary occultation at a distance of 1.5 Neptune radii (R_N) (*3*) but mention no other possible ring or satellite events (*4*).

On 24 May 1981 we observed the close approach of Neptune to a star with the 154-cm Catalina and the 1-m Mount Lemmon telescopes of the University of Arizona observatories. These telescopes are separated by 6 km (east-southeast to west-northwest) in a direction roughly aligned with the Neptune occultation track. The combined signals of Neptune and star were observed with identical dual-channel pulse counting photometers, which digitally recorded data at 10-msec intervals. Time signals from radio station WWV were digitized at the beginning and end of the data records. We used filters that gave wavelength coverage in the red channel of 845 to 930 nm at the 154-cm telescope and 770 to 930 nm at the 1-m telescope. The blue channel at both telescopes covered 450 to 500 nm.

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Table 1. Positions, timings, and red signal drop for the 24 May 1981 Neptune satellite occultation.

Datum	Catalina station 154-cm telescope	Mount Lemmon 1-m telescope
Longitude	110°43′55.1″W	110°47′16.9″W
Latitude	32°25′00.7″N	32°26′33.9″N
Elevation	2510 m	2790 m
Immersion	8 hr, 36 min, 37.8 ± 0.2 sec	8 hr, 36 min, 37.5 ± 0.2 sec
Emersion	8 hr, 36 min, 45.7 ± 0.2 sec	8 hr, 36 min, 45.8 ± 0.2 sec
Red signal drop	4.4 percent	3.1 percent

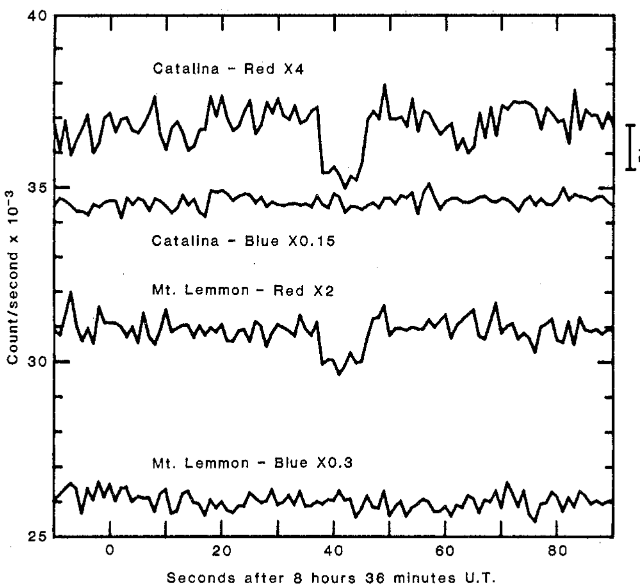

Fig. 1. Red and blue light curves from the Catalina and Mount Lemmon telescopes. The data have been averaged in 1-second intervals. Each signal has been normalized to fit the common ordinate scale. The separate signals from Neptune and the star were independently measured at the start of observations at the Catalina site (see Table 1).

Because of strong methane absorption in Neptune's atmosphere, the planet was quite blue relative to the star, so that a full occultation would produce a drop in the combined signal level of about 4 percent in the red channel but less than 1/2 percent in the blue channel. The blue channel therefore acted as a monitor of transparency and system transients.

Continuous observations, including both Neptune and the star in the diaphragm, were made at both sites for approximately 2 hours centered on 8 hours, 20 minutes UT, the predicted time of closest approach of the star to Neptune (*1*). The earliest observations at the Catalina site were able to separately measure the star and planet, and showed that the star signal was 4 percent of the total signal in the red channel.

Figure 1 shows light curves of an abrupt occultation event that was observed essentially simultaneously at both stations shortly before 8 hours, 37 minutes UT. The data shown are 1-second averages of the magnetic tape data, with time origins independently determined from the taped WWV signals at the two observatories. The event has a depth of several standard deviations in both records at 1-second time resolution and is therefore highly significant. No other such event was found in either data record. Note the continuity of the blue signal, which confirms that the photometer recorded the light from Neptune at a constant level during occultation of the star (*5*).

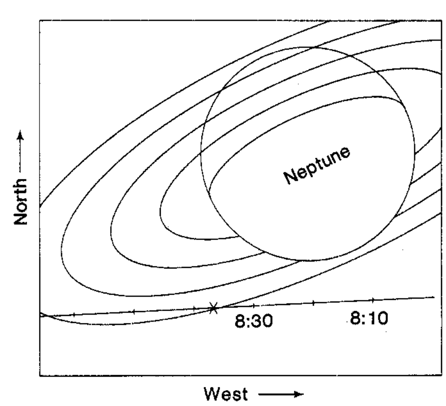

Fig. 2. Geometry of the May 24 appulse as projected on the sky. The predicted apparent path of the star behind Neptune is shown, and the cross marks the location of the occultation. Also shown are loci of constant R_N in Neptune's equatorial plane at intervals of 0.5 R_N.

Table 1 gives telescope coordinates and derived parameters for the observations. The times of contact and depth of the occultation were determined from a least-squares fit of a model light curve to the data averaged to 100-msec time resolution. The model light curve assumes occultation at normal incidence of a star with a projected diameter of 5 km; for the time scales of interest, it differs little from a square wave. As expected, the depth of the occultation was somewhat less in the Mount Lemmon data because the red band pass in that photometer extended farther to the blue, thus including more light from Neptune relative to the star.

The possibility that the occultation was caused by a graze by Neptune's atmosphere can be ruled out because its duration would have to be at least 1 minute for the stellar intensity to be reduced by a significant amount (*6*). A similar argument applies to the possibility of a ring graze. Occultation by a complete ring would necessitate a second occultation by the ring (Fig. 2), which was carefully searched for in the data but not found. Because the event occurred when the predicted position of Neptune was only 2.3 arc seconds from the star, there is a high probability that the occulting body is a part of the Neptune system (the two known moons of Neptune were not near the line of sight). We conclude that the most probable cause of the occultation is a third satellite of Neptune.

For a projected velocity of the Neptune system relative to the star of 22 km/sec, the separation of the two telescopes is equivalent to a time interval of only ~ 200 msec. Thus it is not possible, in view of the noise level of the data, to accurately distinguish orbital motion of the object relative to Neptune, particularly since the size and shape of the occulting body are unknown. It is remotely possible that the observations recorded a chance occultation by an asteroid. However, no cataloged asteroid was closer than 20 arc minutes. A main belt asteroid would have to be at least 50 km in diameter to produce the observed event; it is highly unlikely that such an asteroid (visual magnitude, $m_V = 12$ at opposition) has gone undetected. Photographs of a 3-arc minute field centered on Neptune were obtained on 25 May and show no unidentified objects brighter than $m_V = 17$ (*7*). Only 10 percent of known asteroid orbits would have removed an asteroid from such a field of view.

The predicted circumstances for this

event indicate that the line of sight intersected Neptune's equatorial plane at $3 \pm 1\ R_N$ at the time of the occultation (8). The duration of 8.1 ± 0.3 seconds gives a chord length of 180 ± 7 km if the occulting object moved with Neptune's motion and a minimum diameter of 100 km if it was moving in a direct, circular, equatorial orbit. The abruptness of the change in signal level eliminates the possibility of a grazing contact and limits the maximum diameter to less than ten times these values.

Such an object would have a stellar magnitude of 16 to 20 for an albedo of 0.6 and would have eluded earlier detection because of its proximity to Neptune. Previous examinations of the Neptune system at the University of Arizona reached a limit of $m_V = 18$ to within about 6 arc seconds of Neptune without result. The new object will be difficult to image from ground-based telescopes unless the observed chord is much smaller than the diameter or the object reaches a much greater distance from Neptune than it had when observed by this occultation.

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4. Two weeks before this event, three University of Arizona teams in the Tucson area observed the 10 May 1981 close approach of Neptune to a star. A fourth team collaborated with scientists from the University of Mexico at the Mexican National Observatory at San Pedro Martir, Baja California [*Int. Astron. Union Circ. 3605* (1981)]. Details of these observations are given in W. B. Hubbard *et al.*, *Bull. Am. Astron. Soc.* **13**, 728 (1981).
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7. These photographs were obtained by S. M. Larson with the 154-cm telescope. A wide-field photograph obtained several days later by E. Bowell at Lowell Observatory contained no candidate objects.
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9. We thank S. Tapia and N. Lebofsky for providing assistance at the 1-m telescope, S. Larson and E. Bowell for their supporting observations, and J. Frecker for assistance in data reduction. The photometers were designed and constructed by J. Frecker and E. Roland. This work was supported in part by NASA grants NSG-7045, NSG-7114, NSG-7502, and NGL 03-002-002.

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Photosynthetic Hydrogen and Oxygen Production: Kinetic Studies

Abstract. *Steady-state turnover times for simultaneous photosynthetic production of hydrogen and oxygen have been measured for two systems: the in vitro system comprised of isolated chloroplasts, ferredoxin, and hydrogenase, and the anaerobically adapted green alga* Chlamydomonas reinhardtii [*137c(+) mating type*]. *In both systems, the simultaneous photoproduction of hydrogen and oxygen was measured by driving the systems into the steady state with repetitive, single-turnover, flash illumination. The turnover times for production of both oxygen and hydrogen in photosynthetic water splitting are in milliseconds and are equal to or less than the turnover time for carbon dioxide reduction in intact algal cells. The oxygen and hydrogen turnover times are therefore compatible with each other and partially compatible with the excitation rate of the photosynthetic reaction centers under conditions of solar irradiation.*

A promising approach to the biological production of renewable energy and chemical feedstocks is through splitting of water molecules to produce molecular hydrogen and oxygen by photosynthesis (*1, 2*):

$$2\ H_2O \xrightarrow[\text{light}]{\text{visible}} 2\ H_2 + O_2$$

The important aspect of this reaction is that it stores energy; the available chemical energy of the products is greater than the available energy of the substrate. In biological systems this photoreaction can be driven by light quanta from the visible portion of the electromagnetic spectrum (400 to 700 nm), a range that includes almost 50 percent of the power radiated in the solar emission spectrum. The only known biological systems for direct hydrogen and oxygen production are green algae and blue-green algae. A third, artificial, system derived from these consists of isolated higher plant chloroplasts with associated electron carriers and catalysts such as ferredoxin and hydrogenase. These three systems are known to produce hydrogen and oxygen with visible light (*3–5*) through the reduction of hydrogen ions just as CO_2 is reduced in normal photosynthesis.

Emerson and Arnold (*6*) were the first to measure photosynthesis turnover time, the characteristic time during which biochemistry occurs within a photosynthetic reaction center in preparation for profitable utilization of a second excitation. In the work reported here, the steady-state turnover times for simultaneous light-driven hydrogen and oxygen production were measured by the repetitive flash technique of Emerson and Arnold. These experiments were performed to determine whether the hydrogen and oxygen photoreactions under steady-state conditions are kinetically compatible with each other and with the rate of excitation of photosynthetic reaction centers under normal solar insolation.

Experimental results are presented in Fig. 1. Figure 1A shows data for the in vitro system comprised of isolated chloroplasts, ferredoxin, and hydrogenase [the CFH system (*5, 7, 8*)]. The data in Fig. 1B are for anaerobically adapted *Chlamydomonas reinhardtii*, 137c(+) mating type. [The phenomenon of hydrogen production in *Scenedesmus* was discovered by Gaffron and Rubin (*9*).] The two sets of data shown in Fig. 1 resulted from similar experiments, except that a 3-hour adaptation period of darkness was needed for *Chlamydomonas* (for hydrogenase synthesis) before illumination. Each data point was obtained by driving the CFH system or algae into the steady state through repetitive, single-turnover, flash illumination. The frequency of flashing is indicated on the abscissa of each graph, while the ordinate for each is the absolute yield of hydrogen or oxygen per mole of chlorophyll per flash of light.

The data in Fig. 1 provide kinetic information on photosynthetic water splitting by illustrating the simultaneous photoproduction of hydrogen and oxygen from isolated spinach chloroplasts coupled to clostridial hydrogenase through ferredoxin. If the frequency response of the reactions were linear, both hydrogen and oxygen would reach a constant yield per flash (when normalized to the flash rate). For the data of Fig. 1A, this is approximately true in the frequency range 50 to 150 Hz, although yields decrease at both lower and higher flash frequencies.

Solar insolation values can vary from very low to ~ 1 kW/m^2 (*10*). In higher plants, almost 50 percent of the solar spectrum, from ~ 400 to 700 nm, can be used for photosynthesis. The pigment principally responsible for the capture and conversion of this light energy into chemical energy is chlorophyll, a mole-

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