1.43; $P = .001$. The average loading rate thus increased from 0.037 to 0.179 mg m^{-2} $week^{-1}$ over the 150 weeks of the study.

Figure 1B shows the dissolved nitrate nitrogen (NO_3^--N) delivered weekly to the watershed in bulk precipitation. The data have been log-transformed to reduce the scatter of points. The increase in NO_3^--N (in milligrams per square meter per week) is statistically significant: log (NO_3^--N) = 0.0023 · (week number) + 0.211; $P = .003$). The equation implies an average NO_3^--N loading rate of 1.63 mg m^{-2} $week^{-1}$ at the beginning of the study and 3.60 mg m^{-2} $week^{-1}$ 150 weeks later. This is a difference of 0.141 mmole of NO_3^- per square meter per week.

A mole of NO_3^- derived from gaseous NO_x is presumably associated with a mole of H^+, as gaseous NO_x compounds combine with water to produce HNO_2 and HNO_3 (*8*). Thus the increase in NO_3^--N over the 150-week period would be associated with an increase in H^+ of 0.141 mmole m^{-2} $week^{-1}$. This is exactly sufficient to account for the observed increase in the H^+ loading rates (0.142 mmole m^{-2} $week^{-1}$). The amounts of nitrite nitrogen (NO_2^--N) in our precipitation samples were consistently below 5 percent of the NO_3^--N and can therefore be omitted from consideration here.

The average loading rate for sulfate is 18.0 mg m^{-2} $week^{-1}$ over the 150 weeks. There is a suggestive but not statistically significant ($P > .05$) trend toward increasing sulfate loading rates with time (*9*). Thus, even though sulfuric acid may be a major contributor to total acidity, nitric acid appears to be the component responsible for the observed increase in precipitation acidity.

Our data indicate that the mean acidity of bulk precipitation near the Continental Divide is unexpectedly high and that the acidity of precipitation has increased at a surprisingly fast pace over the past 3 years. The downward trend in *p*H cannot be extrapolated and may even reverse, but it is suggestive enough to deserve careful observation in the future. The low mean *p*H is noteworthy even if the downward trend does not continue, however. No local, sizable sources of pollutants are properly situated to account for this trend easily. Two possibilities are that complex and unsuspected mechanisms are moving pollutants substantial distances from the front-range urban corridor contrary to the prevailing patterns of air mass movement or that very widespread changes in precipitation chemistry are presently occurring in the western United States because of significant increases in the release of nitrogen oxides from multiple sources throughout the West. If the former possibility proves to be correct, our results imply the existence of powerful atmospheric dispersing mechanisms which can move acidic components against strong prevailing weather patterns. If the second possibility proves to be correct, our results imply a very widespread change in precipitation chemistry.

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6. Wet precipitation includes snow and rain with its dissolved and particulate chemical components. Dry precipitation includes all materials accumulating on the collectors during periods when there is no wet precipitation. Large Plexiglas collectors (0.25 m^2) were used so that accurate analysis could be made even for weeks with very limited amounts of wet precipitation. The collectors were mounted 4 m off the ground in clearings shielded by trees and were heated to prevent freezing in winter. The collectors were connected to borosilicate glass bottles with surgical rubber tubing incorporating a vapor barrier. Exposure of distilled water to the collector for extended periods indicated no significant contamination of the sample by the collector. The collecting surface was rinsed weekly and the bottles and tubes were replaced weekly with cleaned, sterilized bottles and tubes. Additional details are given in W. M. Lewis, Jr., and M. C. Grant, *Water Resour. Res.* **14**, 1098 (1978).
7. The *p*H was measured with a Radiometer model 26 meter equipped with a combination electrode and standardized against *p*H 4.0 and 6.0 buffers just prior to use. The sample was then filtered through glass-fiber paper (mean pore size, 2 μm), and the particulate and dissolved components were analyzed separately. Most important to the present discussion are the nitrate and sulfate analyses, but all major cations and anions were included in the analysis (total measured cation input, 1.08 meq m^{-2} $week^{-1}$; total measured anion input, 1.17 meq m^{-2} $week^{-1}$; number of samples = 150). Nitrate analysis was done by reduction of nitrate to nitrite and formation of an azo dye [K. Bendschneider and R. J. Robinson, *J. Mar. Res.* **11**, 87 (1952); E. D. Wood, F. Armstrong, F. Richards, *J. Mar. Biol. Assoc. U.K.* **47**, 23 (1967)]. The sulfate analysis was done by a barium chloride precipitation method [H. L. Golterman, *Methods for Chemical Analysis of Fresh Waters* (International Biological Program Handbook No. 8, Blackwell Scientific, Oxford, 1969)].
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9. This amount of sulfate is equivalent to 0.376 meq m^{-2} $week^{-1}$. The standard error for weekly measurements is 0.041 meq m^{-2} $week^{-1}$, and the coefficient of variation is 121 percent (number of samples = 129).
10. This research was supported in part by the Forest Service, U.S. Department of Agriculture, through the Eisenhower Consortium for Western Environmental Forestry Research (published as Eisenhower Consortium Journal Series Paper No. 29) and by the University of Colorado through Biomedical Research Support grant 153-2281.

11 December 1978; revised 18 April 1979

Direct Measurement of Solar Luminosity Variation

Abstract. *Two rocket flights of an absolute pyrheliometer, separated by 30 months, indicate an increase in solar luminosity (solar constant) of 0.4 percent. The significance of this result is considered in light of the instrument performance during the rocket flights and of pre- and postflight intercomparisons with independently maintained pyrheliometers. There is a high probability that the measured difference is real. Additional observations are required to determine whether the difference results from random fluctuations in solar luminosity, a nonrandom change of short duration, or a sustained change that has climatological significance.*

The energy that determines the earth's climate is derived from solar optical radiation through interactions with the terrestrial ocean, landmass, and atmosphere. Recent models of climate indicate that small, persistent changes in solar luminosity have substantive climatological impact. The magnitude of the effect depends on the model used, but most predict pronounced sensitivity of the climate to changes in solar luminosity (*1-3*).

Evidence from many sources (*4-7*) depicts the earth's climate during the past billion years as nominally tropical, with numerous cyclic excursions to colder periods, some of which were severe enough to cause extensive glaciation from the poles to the middle latitudes. Models predict that such climatological changes can be produced by systematic variation of the earth's insolation by as little as 0.5 percent per century (*8*).

The high sensitivity of the earth's climate to insolation and the probable relations between solar magnetic activity and solar luminosity (*9*) are compelling arguments for long-term monitoring of solar luminosity. This task requires experiment platforms outside the atmosphere and pyrheliometric instrumentation capable of measuring solar flux accurately [that is, with uncertainties in long-term precision (if not accuracy) of no more than 0.1 percent]. The platforms have been available for some time, but the required instrumentation is a recent development (*10*). The experimental re-

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Table 1. Summary of ACR402A rocket-based total solar flux measurements (corrected to 1AU) and comparisons with the PMO2 instrument measurements of Brusa and Froehlich (*14*). The uncertainties, for comparison results, are standard errors (S.E.) of the mean; for solar flux results, they are measurement precision.

Dates	Experiment	Quantity determined	Mean result	Uncertainty (S.E.)
29–31 May 1976	Comparison	ACR402A/ PMO2	1.0047	± 0.0004
29 June 1976	Flight	Total solar flux	1368.1 W/m^2	± 0.5 W/m^2
16 November 1978	Flight	Total solar flux	1373.4 W/m^2	± 0.5 W/m^2
10–13 December 1978	Comparison	ACR402A/ PMO2	1.0053	± 0.0001

sults described here represent what we believe to be the first implementation of both requirements.

Several solar luminosity monitoring programs have been initiated in recent years in which direct measurements of total solar flux are made above the atmosphere. Here we discuss the results obtained with one of the radiometers in a rocket flight program, the confidence that can be placed in them, and their implications for future research. The instrumentation, procedures, and data processing have been described in detail elsewhere (*10–13*).

The rocket program can be divided into four phases. The first was a ground-based comparison, using the sun as a source, between the active cavity radiometer flight instrument (ACR402A) developed by Willson (*10*) for the rocket program and two similar instruments, pyrheliometers PMO2 and PMO5, developed by Brusa and Froehlich (*14*). The comparison was conducted at an observatory on South Baldy Peak near Socorro, New Mexico, in May 1976. It produced results of less than optimum quality due to limitations imposed by site facilities, meteorological conditions, and the short time available to complete the experiment.

The second phase consisted of the direct measurement by ACR402A of extraterrestrial solar irradiance during a sounding rocket flight on 29 June 1976. Three sets of open-shutter solar observations were made during the 300-second period in which the payload was between 100 and 250 km above the earth and aimed precisely at the sun. Between these, two sets of closed-shutter reference measurements established the instrument calibration in situ by substituting electrical power.

The third phase was a second direct measurement of the extraterrestrial solar irradiance by ACR402A during a rocket flight on 16 November 1978, under conditions nearly identical to those of the first measurement. The last phase was a second ground-based comparison of ACR402A and PMO2, conducted at the solar test facility of Table Mountain Observatory, California, in December 1978. The Table Mountain site has well-developed facilities for this type of experiment and a high incidence of dry, cloudless sky. A large quantity of data was acquired under excellent observing conditions, as indicated by Langley plots of sun photometer data (*15*).

The results of the four phases are summarized in Table 1. Values shown for the comparisons are the means of independent sets of observations. The data for each set include a large number of individual measurements. The statistical uncertainty shown for each comparison result is the standard error of the mean of the set. Comparison results for 1976 are a composite of comparisons of ACR402A with PMO2 and PMO5. The PMO2/PMO5 ratio of 1.0012, carefully established by Brusa and Froehlich (*14*), was used to relate all comparisons to PMO2. Comparisons for 1978 include only data obtained for ACR402A and PMO2.

During the three open-shutter solar observation periods and two intervening closed-shutter reference periods of each flight, data were acquired continuously at the rate of 14 samples per second, providing high temporal resolution of ACR402A's performance. The first and third open-shutter periods occurred near the beginning and end of that portion of each flight in which the rocket was pointed toward the sun, when the rate of change of atmospheric pressure within the instrument was maximum. Systematic drifting of 0.1 to 0.2 percent of measured flux was observed, consistent with the effects of pressure change. For this reason, the results from these observation periods, reported elsewhere (*11*), are not included in Table 1.

The total solar flux results given in Table 1 are derived from the second observation period, which occurred near the 250-km peak altitude of the payload trajectory in each flight. Although we believe the effects of pressure changes are negligible during this part of the flight, a small residual downward drift was present in both data sets. The magnitude of drift was close to ACR402A's resolution limit of 0.5 W/m^2 and is consistent with the effect of radiative cooling of instrument surfaces within the sensor's field of view. The data-sampling interval was small compared to the detector's thermal time constant, so not all of the hundreds of data points acquired in each period are statistically independent. The standard errors of the mean results (less than 0.04 W/m^2 for both flights) are, therefore, lower limits of measurement precision. We have chosen to use the observed drift of 0.5 W/m^2 in the total solar flux as a conservative measure of the precision of the results (not their accuracy in the International System of Units).

The most likely explanation for the small difference in the comparison ratio of ACR402A and PMO2 is the lower precision and higher probability of systematic error of the first comparison that resulted from the limitations in that experiment. Pre- and postflight comparisons between flight and reference sensors, an important part of producing results of maximum accuracy and precision, must be performed carefully under optimum conditions.

The total solar flux at 1 AU in 1978 was 0.4 percent larger than the 1976 result. In looking for alternative explanations for a change in solar luminosity, we have considered the possible influence on measured solar flux of differences in the thermal environment of the payload between the two flights. Although the short duration of rocket flights precludes extensive in-flight diagnostic tests, assurance that the instrument is operating in the manner expected is given by the two closed-shutter reference measurement periods. The most important environmental parameter for the ACR402A is the temperature drift rate of its sink, which, monitored with a resolution of 0.03°C, was less than 0.1°C during the solar observation portion of both flights—a negligible source of uncertainty.

The largest difference between the two rocket flights was the earth-sun distance. The earth was near aphelion in June 1976 and near perihelion in November 1978, producing a nearly 6 percent difference in measured irradiance. The ACR402A's linearity, better than 0.01 percent over this range, could not contribute a significant error. The correction to 1 AU is made by assuming an inverse-square relation between solar flux and distance. Although this is not precisely correct (since the sun is not a point source), the uncertainty introduced by the combination of this effect and the uncertainty in the earth-sun distances is much less than 0.1 percent.

The ACR402A sustained a precision of at least 0.1 percent during the period from May 1976 to December 1978, as is demonstrated by the two intercomparison experiments. No evidence indicates instrument performance outside this limit of precision in the two flight experiments conducted on 29 June 1976 and 16 November 1979.

We conclude that a high probability exists that the 0.4 percent change in solar luminosity observed between the two flights is real. Whether this represents a random fluctuation about a constant mean, an isolated change of short duration, or a sustained change that has climatological significance cannot be determined from these results. Additional rocket flight experiments are planned to help resolve this question, but solar monitoring involving the use of free-flying satellites and the space shuttle will be required to assemble an unambiguous long-term data base on solar luminosity. The principal contribution of continuous monitoring will be to establish its secular nature on time scales up to that of the persistence of photospheric faculae (~ 100 days), encompassing a range of solar phenomena with possible links to total luminosity that could lead to an improved understanding of solar physics.

In the future, the space shuttle may provide the optimum basis for compiling a long-term data base on solar flux with the accuracy and precision required to detect subtle trends in solar luminosity, trends that may have climatological significance. The shuttle will provide (i) the opportunity to compare flight and reference instrumentation before and after each mission, (ii) sufficient payload resources available for optimization of flight instrumentation, (iii) adequate flight duration for acquisition of solar data, and (iv) total flight exposure time too short to cause significant degradation of sensors by the environment of space. In addition to providing the climatology data base, the shuttle experiments can calibrate free-flying solar monitors, maximizing the accuracy and usefulness of their results.

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6 September 1979; revised 13 November 1979

Ganymede: Radar Surface Characteristics

Abstract. *Radar observations of Ganymede, at X-band, show that the surface is unusually bright and has unusual polarization properties. A model of the surface based on large numbers of random ice facets (hence vacuum-ice interfaces) is able to account for these characteristics.*

We report here the results of radar observations of Ganymede, Jupiter's largest satellite, at a wavelength of 3.5 cm. Measurements were obtained on six nights in December 1977, using the NASA spacecraft tracking facilities at Goldstone, California.

On each of the nights, we transmitted very narrow beams (0.04°) of monochromatic X-band radiation toward Ganymede for 1 hour and 9 minutes, the round-trip time of flight. During the ensuing 1 hour and 9 minute receive times, the frequency spectrum of the echo was measured continuously, using digital hardware. Altogether, 12 such send-receive cycles were completed, producing more than 2×10^8 individual spectra.

All of the transmissions were right-hand circularly polarized. Reflection from a smooth dielectric sphere completely reverses the sense of circular polarization. Thus, the radar echo would be left-hand circularly polarized were Ganymede a smooth reflector. Echo power in the original, right-hand, polarization sense is normally interpreted as containing information about the roughness of the object. To measure this effect, the receiver was configured to receive right-hand circular polarization on six of the receive intervals and left-hand circular polarization on the other six intervals.

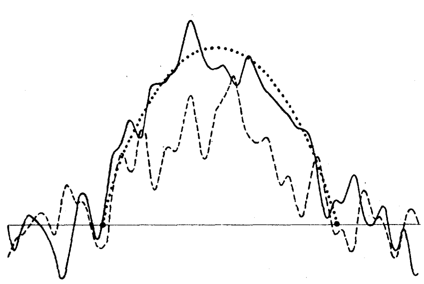

Fig. 1. Spectrograms of Ganymede echoes. Power density is plotted against frequency. (Solid curve) Power in the unexpected polarization, (dashed curve) power in the expected polarization, and (dotted curve) theoretical curve for a perfectly diffusing sphere.

During these measurements transmitter power averaged 343 kW, antenna (64 m) efficiency averaged 44 percent, and system noise temperature averaged 23 K. Although the system noise was extremely low, the power density of the Ganymede echo was always less than 0.007 of the noise power density.

Separation of the weak echoes from the very much stronger background was facilitated by a frequency hopping technique. Every 30 seconds the transmitter frequency was switched, alternately, between two values. On reception, the signal spectra were accumulated in two bins, each corresponding to a transmitted frequency. In this way, one of the resulting spectra served as a very stable baseline for the other.

In order to be sure of correct antenna pointing with such weak signals, we interrupted the observations between each change of configuration between transmitter and receiver and swung the antenna to nearby Jupiter. Jupiter, at a known small angular displacement from Ganymede, provided a very convenient microwave source for this purpose.

The resulting spectrograms, averaged over all of the observations for each of the polarizations, are given in Fig. 1. The full bandwidth processed was 5376 Hz. Dots, spaced 3037 Hz apart, mark the calculated edges of the Ganymede echo spectra. This bandwidth represents the maximum spread of Doppler shifts resulting from the known radius and rotation period of Ganymede. A theoretical curve, included in Fig. 1, gives the spectral shape to be expected if the surface of

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