PROCEEDINGS OF THE WORKSHOP: THE SOLAR CONSTANT AND THE EARTH'S ATMOSPHERE

Held at Big Bear Solar Observatory, North Shore Drive, Big Bear City, California 92314, 19–21 *May* 1975

Edited by
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PLUS = MINUS*

Je mehr
die Sonne scheint
desto mehr
Wasser verdunstet
Wolken erscheinen
und die Sonne
– scheint weniger

Je weniger
die Sonne scheint
desto weniger
Wasser verdunstet
Wolken werden weniger
und die Sonne
– scheint mehr.

da capo

Beruhige dich
das meiste was geschieht
geschieht ohne dich.

Joseph Albers

Poems and Drawings (1961)

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1. Introduction and Summary

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The solar constant has long been a fundamental quantity in astrophysics, but as with many fundamental quantities, interest in its exact value or its variation has not been great over the last decade. This was particularly due to the fact that most models of stars indicated that their luminosity should be quite constant, varying only over nuclear burning times of hundreds of millions of years. Thus, after the pioneering work of Abbott, it has been more a subject of interest for atmospheric scientists who needed to know the exact inputs to the Earth's atmosphere.

In recent years however, the celebrated problem of the missing solar neutrinos has brought into question our theories of stellar structure, and we have begun to think about the solar constant again. Further, current stellar models would have the Sun increasing its luminosity by about 25% in the last three billion years, whereas evidence from the paleoclimate record suggests that the solar constant has been either similar or perhaps even hotter in the past (except for possible blanketing effects in the earth's atmosphere). Thus there is an important astrophysical basis for looking for solar constant variation, both by direct measurement and paleoclimate evidence.

In the meantime, technology has advanced and we can now measure the solar constant with far more accuracy than Abbott could. Observation from outside the atmosphere can normalize ground measurements (and also give the energy absorbed by the atmosphere).

On another side, modelling of the Earth's atmosphere is approaching the point at which the exact value of the solar constant and possible changes become somewhat more critical inputs, so it makes a little more sense today to ask an atmospheric scientist how the atmosphere would change if the solar constant changed by a few percent. Thus the time is propitious to study and measure the solar constant.

In the fall of 1974 the Atmospheric Sciences Panel of the NSF endorsed the idea of an interdisciplinary workshop on the subject of the solar constant, and I was given the job of arranging it, armed with a grant to help bring people together. It appeared that the best results could be obtained by focusing the interest of many disciplines which have an interest in the total radiation from the Sun, all the way from atmospheric sciences to stellar astronomy. A distinguished group of participants was thus recruited from various disciplines, and they came together at the Big Bear Solar Observatory for three days of exchange of ideas. The meeting was most successful; at least we all got to learn something about other people's fields, and it was clear that each field had something important to contribute to the problem. These contributions will be evident from the proceedings which follow. In order to produce rapid dissemination, rapporteurs were appointed who have produced the proceedings, armed with tapes and their own notes. We have only summarized the discussion. In addition, we have appended copies of all those papers presented which were contributed by the authors.* This format enabled the rapporteurs to produce their reports without seriously impairing their scientific activity, and should give a good idea to the reader of the many different pieces of information which were assembled.

Because even this partial description takes 40 pages, I summarize here some of the important points made.

Standard solar models predict a lower solar constant in the past, 75% of the present, 4×10^9 years ago and a virtually constant value over short time scales (10^7 years). However, the lack of observed neutrinos predicted by this model suggests that we do not really understand the interior of the Sun, which means that we cannot rule out solar constant variations on the basis of the theory of stellar interiors. Measurement of the planets, the old Smithsonian measurements, and other data suggest that the Sun cannot have varied more than a few percent over the past hundred years, but some of the measurements even suggest small variation of the order of a percent. On the other hand, in the important near ultraviolet region, there is evidence for some variation in the 2700–3100 Å region and up to 50% variation below 1600 Å, dependent on solar activity.

Present radiometers are capable of measuring the solar constant to an accuracy of a few tenths of a percent, and good values are available for the last solar maximum of 1969, but no measurements have been made since 1969. The best measurements of that period agree within one or two percent with Abbott's measurement, again confirming that there has not been a sizeable variation since 1900.

The paleoclimate data suggests that the Sun cannot have varied by more than 5% in the last hundred million years, but there is fragmentary new data suggesting the temperature may have been 25% higher 3×10^9 years ago. Unless there was some sharp change in the greenhouse effect, this brings into question current views of stellar evolution, at least as they apply to the Sun. The paleoclimate data do show variations of smaller amplitude continually occurring, with some periodicities. The fact that some of these appear to agree with long-term variation of the Earth's orbital parameters which essentially change the solar constant on a seasonal basis (because of the varying distance of the Earth from the Sun) shows that even short-term solar constant variation can be important. Unfortunately, many of these require measurement over very long periods of time, but at least the 11 year solar cycle period is feasible to follow. There is evidence that some of the shorter term variations (over periods of 2500 and 400 years) might be connected with variations in the solar cycle amplitude with that period, as evidenced by historical and tree-ring data.

* In the present report, we have appended only a list of the titles and authors of the contributed papers for which manuscripts were received. Complete copies of these papers are contained in the long version of Big Bear Solar Observatory Report No. 0149, which can be obtained from H. Zirin or from the Atmospheric Sciences Section, National Science Foundation, Washington, D.C. 20550.

So we were left with intriguing possibilities. The possibility of small scale variations, as raised by the planetary and spacecraft measurements of the solar constant and some of Abbott's data, makes high accuracy measurements over a solar cycle important. The fact that there is good evidence for variation in the spectral range producing ozone makes such measurements doubly important. And the possibility of longer term variation points up the importance of good absolute measurements which may be repeated by our descendants. Some felt frustrated that the best instrumentation was not being employed on the current spacecraft measurements, that the cavity radiometers, which make possible absolute measurement were only used on the Mariners in 1966 for engineering purposes and have not been used at all since 1969, and that if we could only get busy on applying these new instruments we might get some short-term results. Dr Suomi pointed out that the time to plant a flower that blooms in a hundred years is now.

So far as circulation modelling is concerned, and the analysis and prediction of effects of solar constant changes, the models are not as good as we would like them. In addition to the solar constant, we also need data on the heat balance (i.e., the irradiance minus the albedo) and the spectrum variation, particularly in the ultraviolet. It also is clear that it is important to get a comparison of measurements of the solar constant outside the atmosphere and at the Earth's surface to determine just what energy the atmosphere is absorbing and where.

At the end of the meeting, the group decided to preserve their interdisciplinary contacts, maintain the mailing list, and perhaps meet again at the next sunspot minimum. At the suggestion of Professor Suomi, a short statement was put together (there was not enough time to work it out to the satisfaction of everyone, but the statement which follows appeared to satisfy most, if not all, the people in the group).

This meeting would not have been possible without the strong support of Fred White, Frank Eden, Bob Manka, and Gene Bierly of the National Science Foundation, the participation of Elske Smith and David Murcray in the Organizing Committee, as well as Joan Walter for the brunt of the organizational problems, and the advice of numerous others on the structure of the workshop. We all were grateful for the fine hospitality of the Big Bear Solar Observatory staff under the direction of Eugene Longbrake and including in particular Alberta Altman, Jack Klemroth, Peter Kupferman, and numerous other friends. The report was produced by the various rapporteurs listed, with Ron Moore taking particular responsibility. This program was supported by Grant DES75-16101 of the National Science Foundation.

2. Statement of the Solar Constant Workshop

The interdisciplinary workshop on the solar 'constant' and the Earth's climate agrees that there is evidence that climate change in the past on scales of a few years to eons could be due to changes in solar irradiance. Such changes would be of great significance to our understanding of the physics of the Sun and future climate change. Accurate measurements of the solar constant with long-term continuity and stability are of the greatest importance; the time to plant a flower that blooms in a hundred years is now. We therefore recommend that a continuous long-term program (essentially a modern continuation of the discontinued Smithsonian program) of solar constant measurement, coordinated from space and the ground, be instituted. We believe that instruments capable of such measurements presently exist, with absolute accuracy of 0.25% and stability 0.1%.

3. Rapporteurs' Summary for each Session

3.1. Session A: the solar background

Chairman: Harold Zirin; *Rapporteurs*: Peter Foukal and William Adams

The meeting opened with a talk by Roger Ulrich discussing first the observational limits to solar luminosity variations. From direct measurements of the solar constant in the past 50 years, paleontological evidence, and the observed scatter in the luminosity of main sequence stars in clusters, he concluded that the Sun may have varied by as much as 10%, but not as much as 20% over the past 10^6 years. Time scales for the Sun are as follows: a few days for the surface, 10,000 years for thermal response of the convective zone, 2×10^6 years for the core (photon duffusion time). Nuclear burning time is 10^{10} years for H, 10^5–10^7 years for He^3 and C^{12}. Ulrich pointed out that standard solar models predict a lower solar constant in the past, 75% of the present 4×10^9 years ago; specifically they would predict flux levels which would be too low to allow liquid water on Earth at an epoch when paleontological records strongly suggest that liquid water was present. The same solar models also predict a neutrino flux which is much higher than the upper limit now being set by the Brookhaven experiment carried out by Davis. Taken together, such discrepancies between solar model calculations and observational evidence indicate a basic lack of understanding of how solar energy is in fact generated. He went on to discuss conceivable means of escaping the dilemma, through models with high mixing, possibly non-radiative energy transport, or incorporating the effect of magnetic field on the efficiency of convection.

Discussion centered on how well established the results of neutrino measurements actually were and on the question of how large the past changes in solar constant actually could be, within the constraints set by paleo-climatological data over the last 10^9 years.

The second talk, by Jack Eddy, centered on the various methods of inferring solar constant behavior over the last 500 years from indirect or 'proxy' solar data. He discussed in some detail the levels of reliability of such solar activity records as coronal appearance during eclipse, incidence of aurorae, sunspot numbers, etc., many of which date back for only a few solar 11 year cycles. Several lines of evidence from such historical records show a significant decrease in solar activity between roughly 1630–1710, an epoch which coincided with the middle of the so-called 'mini-ice-age' which occurred in Europe between about 1450 and 1850.

After a discussion of the theological and psychological influences which may have affected the accuracy of such reporting of solar activity in the past (and in the present), the meeting continued with a talk by Peter Foukal.

He suggested that observations of the solar constant variation over the last 50 years show little evidence for a real (non-atmospheric) variation above the 0.2 percent level. He pointed out that this level of variation is in fact of the order of magnitude expected from the change in fractional area of the solar disc covered by the spots and faculae during the solar 11 year cycle.* It is important that even such a low fractional variation of the total solar constant leads to more direct and more energetically plausible coupling with the terrestrial climate than the observed variation of flux below 1500 Å at about the 10 percent level.

He outlined some work presently in progress to look for direct evidence of the active region contribution to solar variation in the visible and near-infrared.

The discussion continued with G. W. Lockwood's presentation of results obtained at Lowell Observatory from measurements of variation in the light reflected from Titan, Uranus and Neptune. Since 1972, he has been using a new narrow band photometric system improved over the original UBV system used at Lowell by Johnson and Iriarte. He finds surprisingly large changes, greater than 2 percent ±0.5 percent over about a 1 year period in the brightness of these solar system objects, with the largest amplitude of change measured from Titan, and progressively smaller amplitude changes in Uranus, Neptune. Since the accuracy of the measurements increases for the fainter planets, he finds evidence that the intensity fluctuation decreases with distance from the Sun. Lockwood also presented a re-analysis of the older UBV measurements made at Lowell observatory removing individual planet variation, and he finds that they show a significant 2 percent variation over the period of a solar cycle.

J. B. Oke of Caltech discussed absolute measurements of stellar radiation. He pointed out that the main object of absolute stellar photometry was to establish an accurate measurement of the star's spectral energy distribution, rather than its accurate absolute flux, since the latter could not be determined with great accuracy due to uncertainty in the star's distance. He suggested a scheme for tying the absolute calibration of Vega to that of the Sun through comparison of the star with solar light reflected from a satellite of accurately known albedo, to overcome the difficulty due to difference in magnitude between the star and the Sun.

Oke also discussed an intriguing approach to the measurement of variations in the luminosity of stars similar to the Sun in spectral type and age. He suggested observations of close visual double star systems consisting of stars similar to the

* See also E. v. P. Smith and D. M. Gottlieb, 'Solar Flux and its Variations', *Space Sci. Rev.* **16,** 771, 1975.

Sun. Relative photometry of such close systems, he estimated, could yield a relative accuracy of about 0.01 percent.

An extended discussion followed, with mention of other measurements relevant to determining changes in solar luminous output, such as the use of equivalent widths of temperature sensitive lines, and the time variation of solar limb darkening. The significance of Hill's results on the oscillating figure of the Sun was discussed. along with his suggestion that the solar photosphere might be supported partly by a flux of acoustic waves from lower layers.

The focus of the meeting then turned to presentation of results on the EUV variability of the Sun. G. Brueckner reported typical enhancement of about 20% of plage relative to quiet Sun in the wavelength range 1750–2100 Å, with increases of about a factor six for a line such as Lyα. He attempted to calibrate the solar EUV intensity variation against an index of solar activity, such as the Ca II K-line, but with little success. He pointed out that differences in EUV intensity measured over the same wavelength interval at the same time by Solrad and OSO–5 differ typically by up to 40%. This large discrepancy in the satellite measurements made it very difficult to define the true EUV variability. It was also suggested that the Ca II K-line saturates too easily to be a good index of chromospheric activity over the wide dynamic range required by such a correlation.

Discussion centered on the possible effects of the EUV radiation around 1900 Å on the ozone concentration in the upper atmosphere.

Further information on the variation of the solar EUV radiation was presented by Donald Heath. He showed that the amplitude of recurrent 27-day EUV variation decreased from around 50% in a passband including Lyα and the region 1350–1600 Å toward longer wavelengths with a much smaller, but significant, variation measured in the 2750–3150 Å bandpass. He pointed out that the data showed a general correlation in phase but not in magnitude with the occurrence of active regions, with evidence for active longitudes which persist over time scales of years. There was also some indication that a 27-day EUV variation may be caused by fluctuations in solar EUV emission not associated with identified active regions.

M. P. Thekaekara described the history and difficulties of absolute measurements of the solar constant and spectral irradiance since the last century. He pointed out that the scatter between careful measurements of the absolute spectral fluxes by different groups was hardly surprising since fundamental radiometric lamp standards were generally not reliable to better than 10 percent accuracy.

The session drew to a close with a request by W. Wagner for inputs to the design of a solar constant measuring experiment under consideration for the space shuttle. The last presentation was by Adrienne Timothy describing opportunities to carry out observations relevant to the solar terrestrial relationship with instruments on the solar maximum payload.

3.2 Session B; the climate record background

Chairman: James Hays; *Rapporteurs*: J. Murray Mitchell and Gordon Hurford

James Hays introduced the session with a comprehensive review of the principal features of the earth's climatic history in the past million years (Figure B-1).

In the past million years, variations of O^{18}/O^{16} isotope ratios in fossil plankton (from deep-sea cores) have occurred with the clear suggestion of a periodic or quasi-periodic change of order 100 000 years in time scale. These variations are interpreted as reflecting changes in total continental ice-sheet volume, up to 3 times the present-day Antarctic/Greenland ice volume, of order $5 \times 10^{16} m^3$.

In the last 120 000 years the earth passed through a relatively brief period of extreme interglacial warmth (about 10 000 years in duration) into a long interval

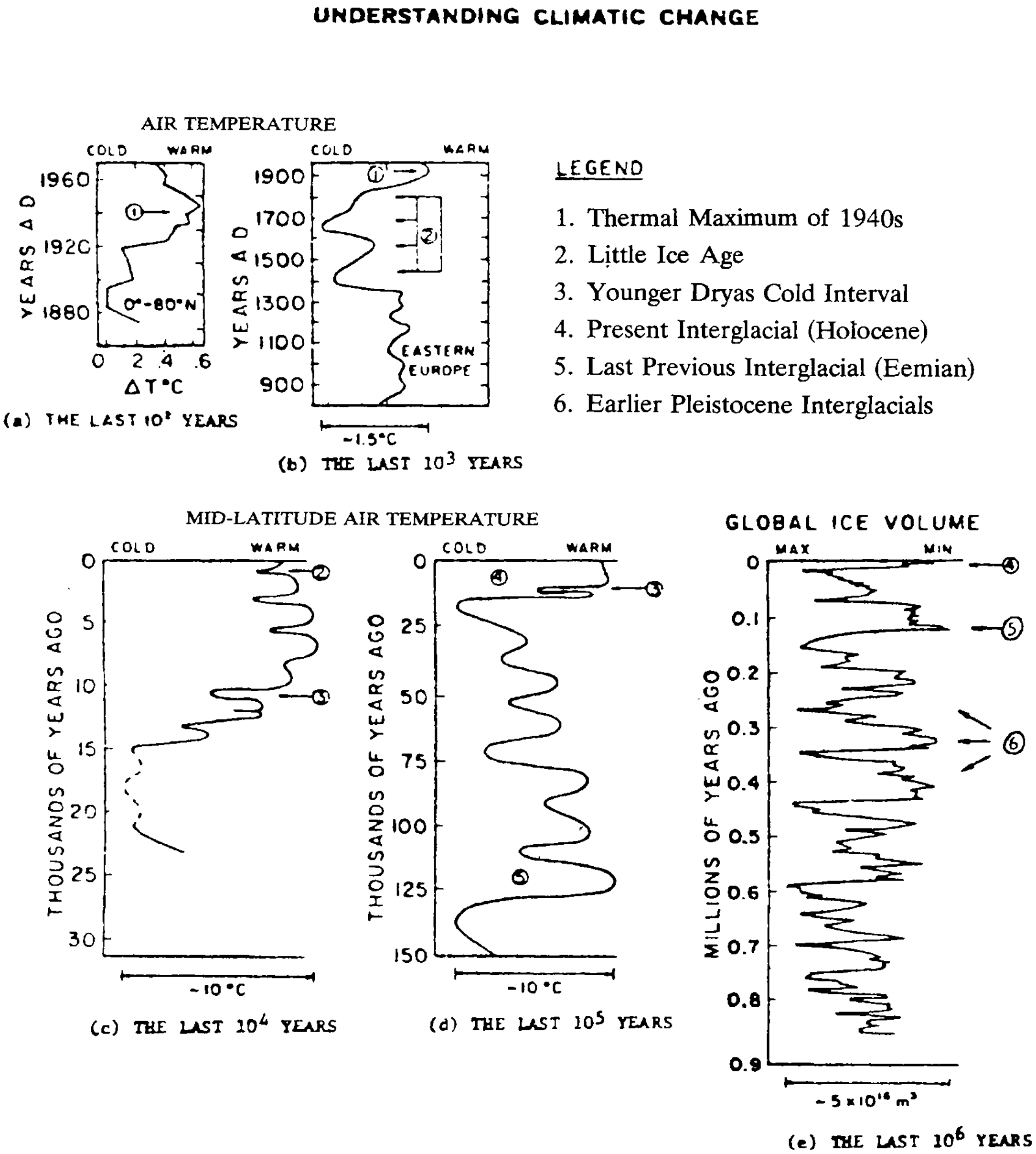

Fig. B-1. Principal features of the Earth's climatic history in the past million years.

of irregularly more and more glacial conditions which culminated in the relatively sudden onset (about 10 000 years ago) of the present interglacial. Between the two interglacials, about 100 000 years apart, variations of ice-sheet volume, sea level, and general temperature levels (up to 10°C in mid-latitudes) appear to have occurred with characteristic periods of variation of about 20 000 years.

Since the onset of the present interglacial, lesser variations of climate have occurred, dominated by a sequence of minor glacial advances and retreats at intervals of 2000 to 3000 years. The last of these minor glacial episodes, known as the 'Little Ice Age', occurred generally from the 15th to the 19th centuries, with minimum temperature levels about 1°C cooler than now, at least in Europe. In the past 100 years, meteorological records indicate that the world underwent a relatively small variation of temperature, of amplitude about 0.5°C, with lowest temperatures in the 1880's and highest in the 1940's. A cooling trend has been dominant in many parts of the world, especially in the arctic and sub-arctic, since the 1940's.

In the climatic variations of the past million years, a tendency toward periodic or quasi-periodic behavior is seen with periods near 100 000 years, 20 000 years, and (in the postglacial period) about 2500 years. The first two of these may be related to Earth-orbital changes; the origin of the neoglacial cycle of about 2500 years, however, is entirely obscure.

Murray Mitchell then summarized his views on the overall problem of climatic change. He remarked that the historical popularity of ascribing climatic change to solar variability seems to have arisen through a fixation on 'visible' external environmental changes, in the absence of any real insight into the capacity for climate to vary through *internal* change mechanisms. The latter insight, in turn, is just now becoming a realistic goal through climate modeling experiments capable of dealing with the climate system in something approaching its full complexity.

The extent to which solar variability may account for climatic variability, on various possible time scales, is not at all obvious from present knowledge of either the Sun or the Earth's climate system. Solar constant changes are but one of several possible ways in which solar effects on climate could arise. Other possibilities include solar UV effects on ozone amount (which can then alter the effective solar constant vis-a-vis the lower atmosphere through changes of ozone absorption of visible radiation), and solar activity effects on the atmospheric electric field (as suggested by evidence of solar modulation of thunderstorm activity).

A wide variety of causal factors may be involved in climatic change, of which potential solar variability is just one factor (Figure B-2). Mitchell presented an estimated variance spectrum of climatic change on all time scales from 10^{-4} years to 10^{9} years (Figure B-3). This indicates a 'lumpiness' of the spectrum on various time scales, including those mentioned by Hays near 100 000 years, 20 000 years, and 2500 years. The spectrum may be quite flat in the range 1 to 100 years, an interval of time scales of special interest in connection with climate prediction.

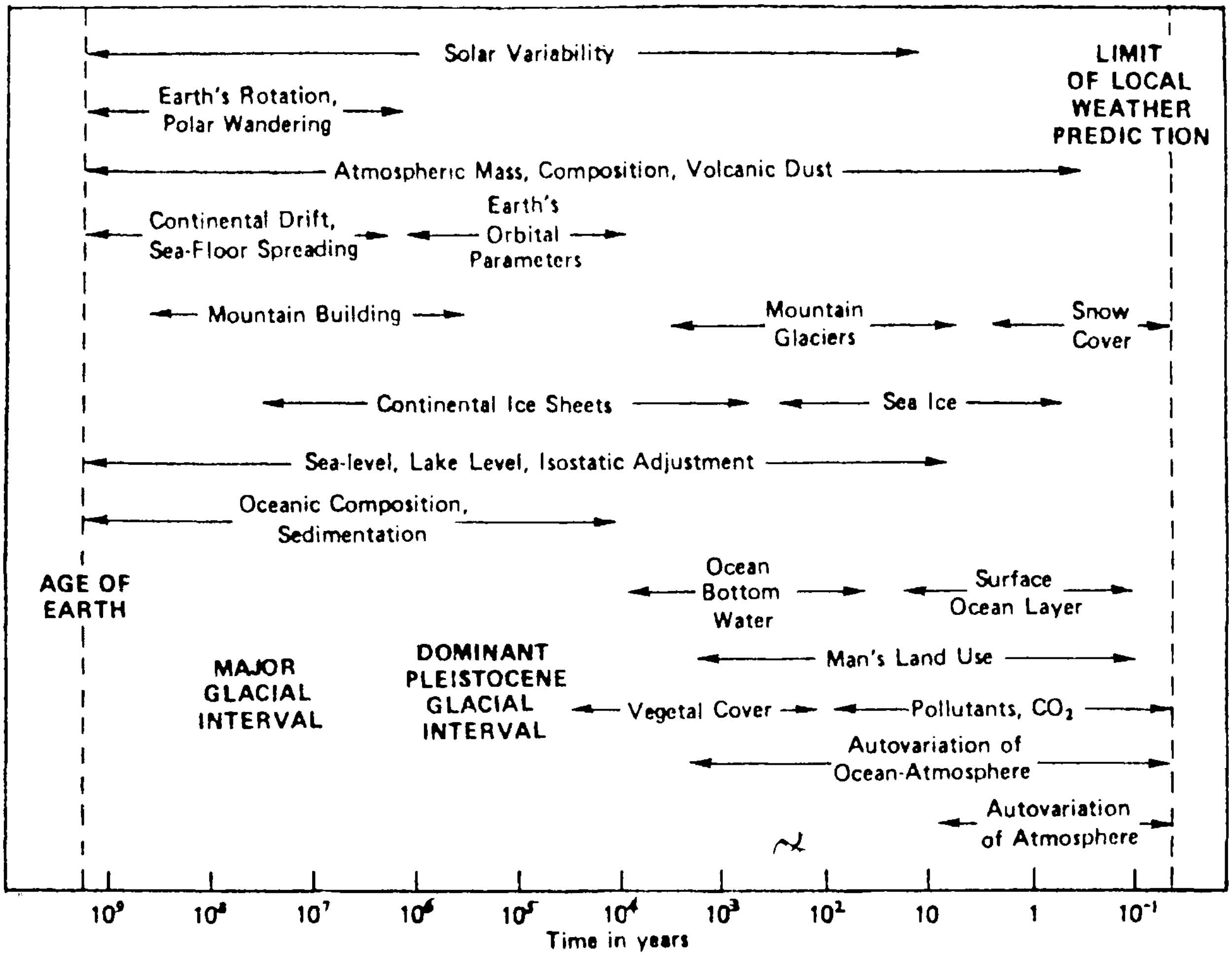

Fig. B-2. Causal factors involved in climatic change.

Potential origins of climatic change were presented by Mitchell (Figure B-4), again as a function of time scale of the change. These were indicated in two groups: internal stochastic forcing mechansims, and external deterministic forcing by a number of environmental factors such as possible solar variability on the scale of the 11-year, 22-year, and longer sunspot cycles. Mitchell stressed the tentative nature of this analysis but suggested that the fraction of total variance of climatic changes accounted for by solar variability is likely to be small, on most, if not all, time scales. To the extent solar variability may be predictable, however, its impact on climate is most important to understand as providing a handle on climatic prediction.

Suomi commented that Mitchell's appraisal struck him as very pessimistic with regard to climate predictability. Robinson said he felt it was rather optimistic! Several participants mentioned the possible solar influence on regional climatic changes. Heath wondered about the cyclic variation in the solar modulation of galactic cosmic rays, as a mechanism for giving rise to solar/climate relationships through ozone and/or atmospheric electric field changes.

Valmore LaMarche outlined some of the evidence for longer-period climatic variations of an oscillatory nature, and discussed the possibility of a connection between solar variation and climate on several time scales. Analysis of the O^{18}/O^{16} isotope stratigraphy in the Camp Century (Greenland) ice core, and of other 'proxy' climatic series, has led to suggestions of climatic variations with periods near 2500 years and 400 years. The 2500-year period is evident in records of alpine glaciation from several parts of the world, during the past 10 000 to 15 000 years. It also tends to be reflected in tree-ring data from the White Mountains of California, which are responsive to temperature and rainfall. Other periodic variations of climate have been claimed by various authors with periods near 1300, 180, and 80 years.

Studies of C^{14}/C^{12} isotope ratios in tree wood have revealed clear evidence of variations of atmospheric C^{14} in the past 7000 years. A major long-term component of the C^{14} variations is attributable to long-term changes of the terrestrial magnetic field, which have modulated the flux of galactic cosmic rays responsible for C^{14} production in the upper atmosphere. Residuals in the C^{14} data appear to reflect a weak 11-year sunspot cycle component, with a lag of a few years after sunspot number variations consistent with theory if heliomagnetic changes accompanying solar activity are involved. Comparison of the C^{14} record with historical temperature variations reveals a rather consistent relationship, with low solar activity (and high C^{14} production rate) associated with low global temperature

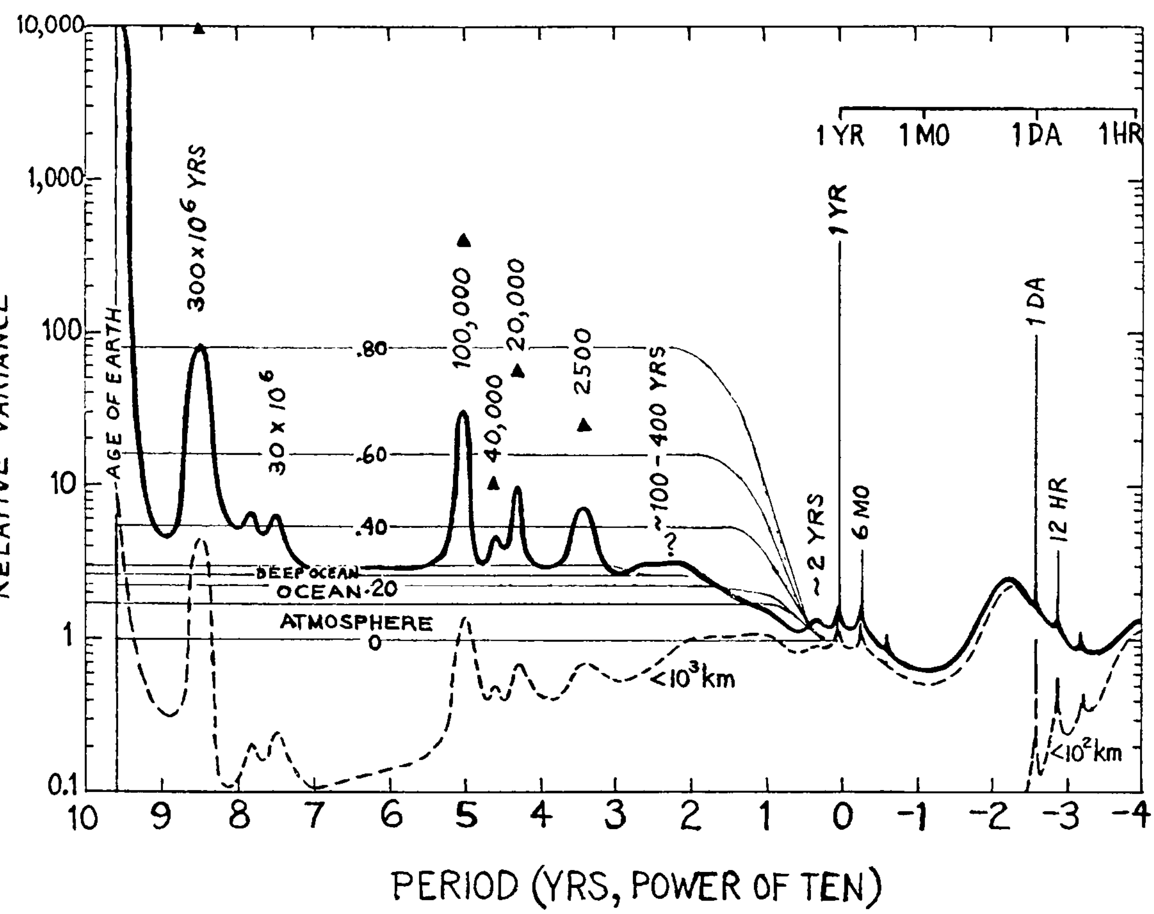

Fig. B-3. Estimated variance spectrum of climatic change.

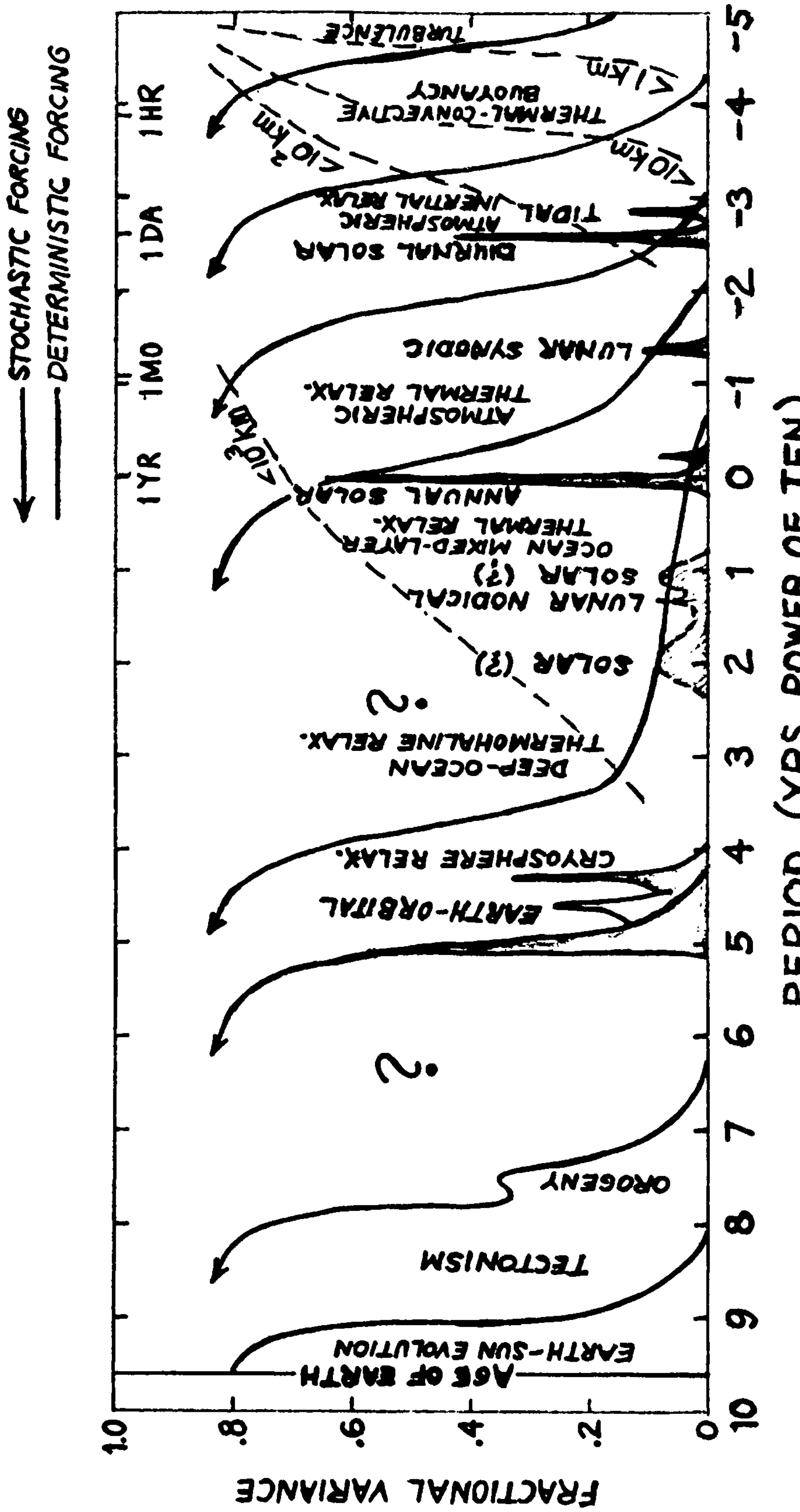

Fig. B-4. Potential origins of climatic change as a function of time scale of the change.

levels, and vice versa. The Little Ice Age, for example, was a period of high C^{14} levels in the atmosphere, and of low solar activity.

LaMarche concluded by emphasizing the need for caution in interpreting C^{14} variations as a reliable indicator of solar activity, and in accepting all apparent periodic variations of climate at face value.

Elske Smith noted the possibility of cosmic ray events associated with supernovas, such as might have followed the Crab Nebula supernova of 1054 A.D. It is not clear, however, whether such events could be detected in the C^{14} record, nor indeed whether the cosmic rays from the Crab Nebula (if any) would yet have arrived in the solar system.

Glen Shaw recalled that some evidence of increases in microparticle content of polar ice, at intervals or order 2500 years, had been noted in the studies of Lonnie Thompson at Ohio State.

Samuel Epstein then explained how isotopic variations (of both oxygen and hydrogen) can be used as reliable indicators of paleoclimatic temperature variations. He described how isotopic enrichment of both O^{18} and D in precipitation can arise (relative to their concentrations in sea water) and noted that, in foram carbonates, O^{18} enrichment (relative to sea water) is a function only of temperature in the habitat of the (living) forams, which can then be recovered from deep-sea sediment analysis.

Epstein presented data on the deuterium isotope variations found in tree-wood cellulose from White Mountain (California) Bristlecone Pine, from 1000 A.D. to the present. This is a reliable measure of paleoclimatic temperatures because D in cellulose is not exchangeable. A power spectrum of the Bristlecone Pine D variations revealed a rather prominent peak at 22 years, and another peak of order 500 years in period. A similar analysis of *pinus silvestri* from Loch Affric in Scotland also showed a modest spectral peak near 22 years, as well as (also modest) peaks near 16 and 11 years. Further O^{18} data were presented for ice cores from Greenland and Antarctica, which could be calibrated rather precisely in terms of paleoclimatic temperatures.

Epstein showed some O^{18} analyses of Jurassic Belemnites, which reveal seasonal variations of temperature comparable to those of today in various parts of the world, and of both benthonic and planktonic foram records from the tropical oceans spanning the past 80 million years. The latter indicate that ocean surface temperatures decreased from about 24°C to about 18°C in the past 80 million years, whereas the ocean bottom temperatures decreased from about 13°C to near 0°C in the same time period. He concluded by showing analyses on marine cherts (SiO_2 $(OH)_x$) which indicate systematic decreases of paleotemperature in past aeons of the Earth's history on the basis of measurements of both D and O^{18} in the cherts. Further analysis of this kind is planned which may shed light on the evolutionary thermal history of the Earth, and help to establish limits on the variability of the solar constant on the longest time scales of interest in solar physics.

3.3 Session C: Measuring the Solar Constant

Chairman: Keith Pierce; *Rapporteurs*: O. R. White and Barry LaBonte

Dr D. Labs began a review of solar constant measurements by noting that attempts to measure the solar constant go back at least to Father Angelo Secchi who tried the measurement in Rome in 1866 and decided the 'surface temperature' was (5 338 519+273) K! Modern solar constant measurements may be classified as ACTINOMETRIC (broad-band, non-selective receiver) or SPECTRAL (measured as a function of wavelength and then integrated). Actinometric instruments employed in the past include the Abbott water-flow pyrheliometer, Angstrom pyrheliometer, Multichannel filter radiometer of the Drummond type, Cone radiometer, the Hy-Cal normal incidence pyrheliometer, Active-cavity radiometers, and the temperature control flux monitor.

He pointed out that one cannot use Bouger's law of atmospheric extinction in broad-band, actinometric measurements of the solar constant because individual treatment of each wavelength is required. Since the early 1960's attempts have been made to measure the solar constant by the actinometric method from outside the Earth's atmosphere in aircraft, ballons, rockets, and satellites. At aircraft altitudes of 10 to 12 km one is above 99% of the water, and 20% of the mass of the atmosphere as a whole. At balloon altitudes most (but not all) of the O_3 is below the platform, although corrections are required for residual absorbers and scatterers still overhead.

Spectral intensity measurements may be made from lower altitudes, such as mountain tops with accurate correction for atmospheric extinction. These corrections are made by extrapolation to zero air mass, where signal in a narrow spectral band is plotted against airmass during a day's observation. Under good conditions, the extraterrestrial intensity (in the infrared in bands between principal atmospheric absorption features) can be determined by this method to 0.5%. In any case, when the measurements are done carefully from good stations (such as the Jungfraujoch) and when care is selected in choosing the day of observation, extinction is not a serious handicap to the measurement of the solar intensities, in Dr Labs' opinion.

Dr Labs feels that the ideal platform for the measurement of the solar constant would be a man-controlled platform *above the atmosphere*, with inflight calibration, on a manned vehicle such as SPACELAB.

Dr Thekaekara commented on the curious fact that the measurements by different observers of the solar constant at any one epoch always seem to cluster in close agreement, even though the 'agreed upon' value seems to change from time to time. He speculated that this may be psychological. Dr Fröhlich described the International Pyrheliometer Scale (IPS) as an arbitrary compromise calibration of two scales which gave different readings for the solar constant. These were the Smithsonian (Abbott) scale and the Angstrom scale; they differed by about 3.5%. In 1956 a compromise scale was adopted which lay about halfway between these values.

Dr Heath asked how corrections are made (in ground-based measurement of the solar constant) for variable ozone amounts and for variable turbidity. Answer: One avoids the spectral regions of strong absorption.* Similarly, one avoids the problems of turbidity by making observations only on clear days when the turbidity is *very* low.

Dr Neckel spoke on the accuracy of solar radiation measurements and the need for consistency of all radiation data.

He began by explaining that there are two basic systems of solar radiation data, different in their method of observation and in their customary uses. The first, concerning the solar constant and spectral irradiance, is taken from platforms above the earth and is used as NASA standards and by the American Society for Testing Materials. The second system is based on observations taken from mountaintop stations, as by Labs and Neckel, and is more commonly used by astronomers. The solar constant integral obtained in the two methods agree closely: the NASA value is 1.94 calories cm^{-2} min^{-1}, the Labs and Neckel value 1.95 calories cm^{-2} min^{-1}. However, the differences in spectral irradiance become significant and can amount to as much as 10 or 20%. Dr Neckel summarized several points in comparing the relative advantages of the two methods:

(1) The NASA value comes from aircraft measurement at an altitude of 12 km; the Labs and Neckel data from mountaintops from 3 to 4 km. The apparent advantage of the higher altitude for aircraft is offset by the facts that the aircraft flies through changing atmospheric conditions due to its rapid ground speed during a measurement and that restricted time prevents accurate determination of instantaneous extinction. Also the aircraft window restricts the spectral band.

(2) The ground based measurement is made by a method of relative photometry (Sun vs. std) which enjoys the same advantages as relative star photometry in which accuracies of ±1% can be achieved. The accuracy of the mountaintop measurements of solar radiation is thus in principle capable of ±1% accuracy.

(3) Measurements of the spectral distribution of solar radiation from mountaintops do a better job of matching theoretical models of the photosphere as well as the colours of Sun and G2V stars than do measurements from aircraft, according to Dr Neckel. (The terminus technicus 'colour' is used in astrophysics for quoting the ratio of broad band flux- (irradiance-) values observed in two different wavelength regions in a logarithmic scale:

$$\text{colour } `B - V\text{'} = 2.5 \log\left[\int \mathrm{I}(\lambda)\mathrm{V}(\lambda)\,\mathrm{d}\lambda \Big/ \int I(\lambda)B(\lambda)\,\mathrm{d}\lambda\right],$$

where $B(\lambda)$ and $V(\lambda)$ = transmission of filters defining the passbands 'B' and 'V'.)

* (a) No observations for $\lambda < 0.33\ \mu$m because of strong ozone absorption (neither from ground nor from an altitude of about 12 km).

(b) In the region $0.5 \leq \lambda \leq 0.7\ \mu$m the ozone absorption can be determined from the Bouger-line (see for example D. Labs and H. Neckel: *Z. Astrophys.* **65,** 133 (1967), Figures 3, 4, 5).

(4) Mountaintop measurements typically look at the center of the solar disk, rather than at the whole Sun, as do the aircraft measurements. Dr Neckel pointed out that it is a simple matter to correct a central-disk measurement to a whole-disk value. The accuracy of radiance standards, which is known to be significantly better than that of standards of irradiance, was demonstrated in slides.

A question was raised about the benefit of demonstrating agreement with theoretical models of the photosphere since these change so rapidly and since our understanding of the photosphere is far from complete. In answer, Dr Neckel pointed out that all recent model continua in the relevant regions do not in fact differ significantly. Dr Hall questioned the matching of the Labs and Neckel data on the infrared end; Dr Neckel acknowledged that the infrared irradiance could be somewhat less accurate; they utilize the Pierce limb-darkening data. Dr Hall noted that more recent measurements on the near infrared show the older limb-darkening data may be as much as 2% to 5% in error.*

In the next talk, errors inherent in ground-based observations of the solar spectral irradiance were described by Glenn Shaw. In particular he stressed that the Langley extinction curves of photometer output versus air mass may be influenced by non-linear effects of water absorption and diffuse aerosol scattering. Pollutants and airmass change may produce temporal variations in optical depth. Atmospheric effects can be removed to the 0.1% level by more accurate theoretical treatments, and by measurements of atmospheric parameters simultaneous with solar constant observations.

The opinion expressed during the discussion that these effects were too small to be significant was countered by emphasizing that we are interested in greater accuracy in variations of the solar irradiance, even though one percent may suffice for the absolute values. Such factors as the stratospheric dust veil and the necessity to observe to large airmass values imply that these effects cannot be dismissed out of hand.

G. Robinson discussed the issue that the meteorologist requires solar spectral irradiance, rather than the integrated irradiance. Especially necessary are the values in the wavelength bands where the radiation is absorbed at Earth, such as the wavelengths bands of H_2O and ozone. The absolute spectral irradiance need only be accurate to $\sim 2\%$, but discrepancies between astrophysical and meteorological values are as large as 5% in the infrared H_2O bands. Further, observed values of the solar illuminance vary by 15%, possibly due to the Chappuis band.

Discussion of the H_2O band problem centered on possible errors in the band profiles, and the inter-band opacity; both are certainly important at the 0.1% but not the 5% level. The issue of the illuminance was not further resolved.

Dr C. Fröhlich presented a critical review of measurements of the solar constant carried out over the last decade. As a result of an analysis of the

* N.B.: These possible errors concern the radiation near the limb, the corresponding corrections for the ratio of mean to central intensity (F/I) would be much smaller ($\leqslant 1\%$).

TABLE C-I

Summary of revised direct measurements of solar constant.(Accuracies are only given for the SI instruments, because of the difficulty to estimate an accuracy for representation of IPS.)

Author	Value mW cm^{-2} SI	IPS	Correction	Main reason for adjustment
Kondratyev, Nikolski	—	133.6	−1.2%	Interpretation of results
Duncan, Webb	—	134.0	−0.7%	Calibration
Kruger	137.2±2.7	—	+1.0%	Interpretation of results Calculation of cavity absorptance
Murcray	—	134.7	+0.7%	Calibration
Kendal	137.3±1.1	—	+0.2%	Calculation of cavity absorptance
Willson	136.6±0.8	—	0.0%	No adjustment
Plamondon	136.1±1.8	—	+0.6%	Calculation of cavity absorptance
Mean:	136.8	134.1		
Difference:	2.0%			

instrumental, calibration and reduction errors Fröhlich arrived at revised values for several published values (see Table C-I). He showed that several good measurements give 136.8±0.27 mW/cm^2. The good agreement of these well-calibrated measurements suggests that this result is reliable. The difference between the revised determinations based on the SI and the IPS (International Pyrheliometric Scale) is 2%, which corresponds to a discrepancy between the IPS, which is essentially arbitrary, and measurement by absolute instruments such as the cavity radiometer.

Fröhlich pointed out the importance of calibrating the reflectance of the actual cavity particularly because Parson's Black, used on some radiometers, shows significant retroreflectance; 3*M* black does not show this but it, too, must be calibrated. Parson's has different properties if sprayed or brushed. Robinson said Parson's Black had been introduced in response to his request for a *grey* paint.

The reliability and consistency of different types of instruments was discussed by several persons. Thekaekara pointed out that Angstrom pyrheliometers degrade in space, while Willson cited the unreliability of Hy-cal instruments for solar constant measurements since they are not absolute. Active cavity radiometers appear to be the most reliable currently available.

R. C. Willson discussed the development of the JPL series of cavity radiometers based on variants of the PACRAD instrument developed by Kendall. Before describing his own radiometers he mentioned Plamondon's transducer cavity measurements of the solar constant made from Mariners 6 and 7 over a time span of 1.8 years. Both radiometers showed steady temporal degradation, due to stressing of a platinum resistor; after correction for degradation, a steady signal was found, with short-term variations, possibly real, of 0.2%. These data were felt to be important and worth reduction.

The active cavity radiometers developed by Kendall and by Willson are devices of high stability capable of measuring the solar absolute irradiance with an accuracy ±0.5 mW cm^{-2}. Comparison with the International Pyrheliometric Scale (1956) indicates that the IPS standard is 2.2% too low. These instruments have been flown on two balloons for the purpose of measuring the solar constant in 1968 and 1969. The values obtained are, respectively, 137.0 and 136.6 mW/cm^2 with an estimated absolute uncertainty of ±0.5%. Further improvement to an absolute accuracy of 0.1% seems technically feasible at the present time.

In the general discussion of this approach it was pointed out that such radiometers have no inherent spectral limitations when used without entrance windows. Questions on the influence of interplanetary dust and atmospheric absorption in the JPL solar constant measurements were asked. The zodiacal light contribution is probably at the 10^{-9} level and is, thus, undetectable. Corrections for gaseous absorption in the upper atmosphere were made. Ozone appears to be the major contributor with some variation in time.

Following on the original 1951 measurements on Mt. Lemmon, Dunkelman plans to reinstitute his measurement program at the new Lunar and Planetary Laboratory site in the Catalina mountains near Tucson. The type of instrumentation is a double monochromator fed by a diffuse source illuminated either by the Sun or a tungsten reference lamp. The main objective of the program is measurement of the solar spectral irradiance and study of the atmospheric extinction due to ozone. Spectral regions near the ozone cutoff below 3300 Å and in the Chappius band (5000 Å to 7000 Å) of ozone are of particular importance. The previous experiments showed the typical problems with the time variation in the air mass corrections. Dunkelman indicated that he may use a calibrated detector to avoid the use of a standard lamp.

J. Kendall described his PACRAD cavity radiometer. Important features include matching of the hot and cold junction time constants and correction for the temperature sensitivity of the wire wraps. Measurement of the Stefan-Boltzman constant demonstrates absolute radiometer accuracy of 0.3%. Six aircraft observation runs give a solar constant of 137.3 mW/cm^2, with no detectable variation over a 3 week period. The radiometer has also been used with an external occulting disk to measure the solar aureole.

A question was raised as to the true precision of the Stefan-Boltzman measurement, since the temperature scale is itself uncertain.

3.4 Session D: what happens to the atmosphere?

Chairman: J. Murray Mitchell; *Rapporteurs*: G. Robinson and Ron Moore

The chairman, J. Murray Mitchell opened the session by noting that the purpose of this session was to discuss what solar variations, if any, might do to the atmosphere, and what would be the resulting effects on the weather and climate. He pointed out that the study of this question is mainly by climate 'models'.

In the first talk, Haurwitz discussed the Rand 'black cloud' experiment with the Mintz–Arakawa GCM in which the solar constant was decreased by 6.5 percent. The major model constraint is fixed sea surface temperature. Three 60-day runs were made.

(i) Control experiment with solar constant 2 Langley/min.

(ii) 'Black cloud' – solar constant reduced by 6.5 percent, other conditions as control.

(iii) Control experiment with solar constant 2 Langley/min but random perturbation of initial temperatures.

Reduction of solar constant led to reduced temperatures from about 45°S to 45°N. At higher latitudes the differences between the three runs were not systematic. Wind velocities also showed a substantial decrease in low latitudes. Equilibrium was not reached in 60 days.

In response to Haurwitz's talk, Quirk commented that a similar reduced-solar-constant experiment with 2-week runs with the Goddard model showed no obvious effect on weather patterns (e.g. storm tracks).

In the second talk, Sellers explained the nature and some of the implications of the radiation-balance type global models introduced by Budyko and himself. The first type simulates the annual mean zonal heat budget by an equation of form

$$Q_j(1-\alpha_j)-I_j=\Delta F_j,\ \ F_j=-K(\Delta T_0/\Delta Y)$$

where Q_j is the solar input in zone j

α_j the zonal mean albedo

I_j the output terrestrial radiation

ΔF_j the divergence of advective heat flux

T_0 the surface temperature

K an 'eddy diffusion coefficient' type transport parameter, which could be $K(T_0)$

$\Delta T_0/\Delta Y$ latitudinal gradient of surface temperature

With all terms expressed as $f(T_0)$ the equation is of form $\Delta(T_0)=f(Q)$. Major results found with this model are:

(1) For a given solar constant Q there are three possible distributions of T_0 (climate):

(a) The present climate

(b) A completely ice-covered Earth

(c) An intermediate state with ice to around 30°–40° latitude.

(2) The decrease from the present Q required to produce an ice age depends on parameterization, but is 2 to 5 percent.

(3) Once the ice-covered Earth condition is achieved a 30–40 percent increase of solar constant is required for change. There is then a transition to a completely ice-free regime.

(4) The model is fairly insensitive to changes of K. If K is increased with fixed

solar constant

(a) the ice edge moves poleward,

(b) but so does the critical latitude at which an ice advance induced by decreasing solar constant becomes irreversible without further solar constant decrease,

(c) the model becomes more sensitive to a change in solar constant.

Sellers then described an even simpler model in which the equation is integrated over the globe:

$$S = \frac{4\bar{I}}{(1-\bar{\alpha})}$$

S is the solar constant
I the mean outward flux of terrestrial radiation
$I = f(T_0, n)$ where n = cloud cover
$\bar{\alpha}$ is the global mean albedo = $\phi(n, t, r, \alpha_0)$

where t, r are atmosphere transmittance and reflectance, and α_0 the surface albedo.

This is solved for the solar constant S, which produces the climate characterized by T_0, n, t, r, and α_0, α_0 itself being a function of snow cover and, therefore, of T_0. A set of solutions for different $\bar{I}$ functions was exhibited. (See Figure D-1). The

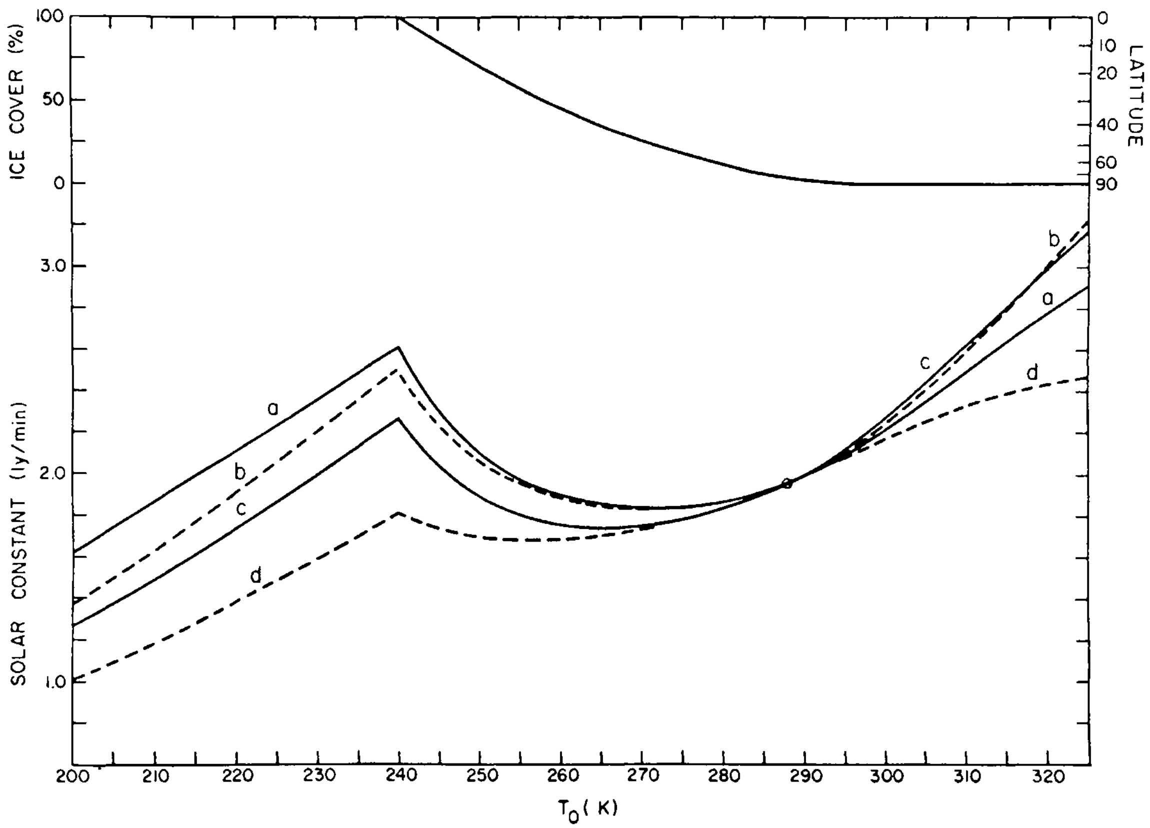

Fig. D-1. Relations between the solar constant, the Earth's surface temperature T_0, and the percentage of ice cover for Sellers' global-averaged models.

global-average model leads to the same major conclusions as the zonal-average model.

Someone asked if a jump from a partially ice-covered Earth to a completely ice-covered Earth would occur at the point when it began to snow in the tropics, which would drastically increase the average albedo of the Earth. Sellers pointed out that such effects weren't contained in his model. This is because parameters such as the average albedo are smooth, rather slowly varying functions of the surface temperature T_0.

Another point of discussion was the probably large effect of clouds. Sellers had simply assumed a constant 50 percent cloud cover in his model, and he pointed out that the dependence of cloud cover on surface temperature or on the solar constant was just not known. It was suggested that it would be interesting to experiment with the model making different plausible assumptions about the dependence of cloud cover on T_0 or S. It was also suggested that some idea of the relation between T_0 and cloud cover might be gained from satellite data on zonal cloud cover. Sellers responded that such local or zonal correlations between surface temperature and cloud cover might be essentially different than the dependence between global averages of T_0 and cloud cover.

A question was raised as to the physical reality of the part of the $S - T_0$ curve where T_0 decreases with increasing S. Sellers pointed out that dynamic models have been found to be unstable in this region, which indicates that the actual climate would always be such that T_0 would increase with S.

Epstein commented that the observed isotopic composition of the polar ice shows that the tropics to pole temperature difference has always been substantial. One cannot make the ocean too cold as an ice age builds up – surface temperature has probably not been as low as 10°C for evaporating regions in the tropics.

In the third talk, Suomi reported some of the conclusions of the recent GARP Symposium in Stockholm on requirements for climate modeling. Observations required fall into three classes – firstly, detailed observations required to improve parameterization of sub-grid-scale processes; secondly, control observations required for verification of model performance – these must be global and on a wide range of time scales; and thirdly, observation of external parameters. In the first class were included observations of the modification of radiation by the atmosphere, in the second class observations of the global radiation budget, in the third class observations of solar input and of any changes in the solar spectrum.

The Stockholm statement called for observation of both solar irradiance and the net flux of solar radiation at the top of the atmosphere with an accuracy of $2\,W/m^2$. Suomi's comment – no way. Accuracy of 10 percent was suggested for solar spectral irradiance. In reply to questions (Brueckner) Suomi indicated that this was the order of accuracy which could significantly affect the energy balance in the present rather crude climate models.

Suomi proceeded to comment on some problems of satellite measurement of Earth radiation budget. The requirement is for net input/output of radiation as a function of latitude, at a height about 30 km. There is a spatial resolution problem and a sampling problem, the latter particularly serious for solar radiation because of the diurnal variation both of the solar radiation and of cloud mass. Sampling at a 6-hr interval means about 10 percent error in reflected solar radiation, 1–2 percent error in terrestrial radiation.

Suomi believes that we could now measure the solar constant from satellites with good long-term stability and accuracy of a few tenths of one percent. He suggested a resolution recommending early start of such measurements.

In discussion Smith regretted the absence of experts on the atmospheres of other planets and was assured that these objects were receiving the attention of terrestrial climate modelers. Quirk suggested the possibility of a one-time measurement of the solar constant to 0.1 percent followed by a surface-based monitoring program. Brueckner returned to the question of the accuracy of observation required in the far UV. General consensus was that much higher accuracy than 10 percent was almost certainly needed to understand mesosphere and high stratosphere photochemistry.

The fourth talk was given by Kaplan. He first addressed Brueckner's question on need for detail at $\lambda < 2000$ Å. He considered that high accuracy in very great detail is needed for some photochemical problems, particularly O_2 dissociation, e.g., resolution $\Delta\lambda = 1$ Å or better in the Schumann-Runge band. Atmospheric transmission in this region also requires detailed study; e.g., of resonance scattering and non-LTE line intensities.

Kaplan then presented material on an experiment with the NCAR/GCM which illustrates a significant difference in the dynamics developing in two runs which differ only in the degree of sophistication of the treatment of the radiation terms. Ozone was not included in this experiment and Kaplan put forward qualitative arguments suggesting that its inclusion would increase the discrepancy with the real atmosphere for the standard model and decrease it for the more sophisticated model. He considered that O_3 might provide a positive feedback destablilizing mechanism in the upper tropical troposphere.

Foukal asked what would be the relative importance of O_3 and H_2O in the dynamics of the atmosphere for a change in the solar constant. Both Kaplan and Quirk said that their models suggested that the two effects would be comparable. However, neither Kaplan's model nor Quirk's model takes stratospheric dynamics into account adequately.

In the fifth talk, Leith described some aspects of the climate program at NCAR. There has been development of Sellers-type models and studies of their properties. These confirmed the properties described by Sellers earlier in the session. Leith stressed that the models were of an equilibrium state and did not address the question of the rate of approach to equilibrium. This rate would be controlled by properties of the atmosphere and, particularly, of the ocean. The time constant might be of order 1000 years.

Leith then discussed the contribution of General Circulation Models (GCM's) to climate research. GCM's are concerned with the evolution of detailed states of the atmosphere, and in addition to prohibitive economics there are physical, mathematical, and statistical problems connected with longterm simulation by GCM's. They throw some light on the real life problem of defining climatic change – how to detect a 'real' change, perhaps one connected with variation of an external parameter (e.g., the solar constant) from the 'noise' of the day-to-day weather fluctuations – the detail considered by the GCM's. A required parameter is the standard deviation of a time average of a meteorological variable in terms of the standard deviation of the individual values of the variable (the time average being a typical climatic variable). Leith commented that time averaging is a very inefficient filter of the day-to-day fluctuations. It has been found very difficult to get significant 'climate change' in mid-latitude perturbation experiments with the model. A small perturbation will lead to different 'weather' after about a week, but no change of 'climate'.

Leith offered as an alternative and more promising approach the study of statistics of the present atmosphere, particularly time-lagged correlations $R(\tau)$, in the hope of establishing the utility of analogies with classical statistical mechanics. He spoke of the fluctuation dissipation theorem which relates the recovery from perturbation of a system near equilibrium to the natural fluctuations, specifically to $R(\tau)$ in a conceptually simple equation. However, for a multivariate system a matrix equation is required, and Leith casually mentioned 1000 degrees of freedom.

In the discussion following Leith's talk, it was pointed out that the statistical approach suggested by Leith for predicting the response of the atmosphere to an 'applied force' (e.g. a change in the solar constant, or increased dust due to a volcanic eruption) would only work if the correlation $R(\tau)$ of the present atmosphere converges. It was also noted that if anything analogous to the fluctuation dissipation theorem holds in the atmosphere, then linear regression for forecasting models should be the most adequate attainable for long-range and climate forecasting. Experience with these to date is not encouraging.

The remainder of the afternoon became mostly a discussion of available data on solar radiation at the surface and, secondly, of what to do and how to do it, regarding measurement of the solar constant preliminary to Session E on Wednesday morning.

Hanson called attention to Kimball's compilation of direct solar intensity measurements ca. 1880–1920. There is no comparable record of scattered radiation. He discussed the standardizing history of the U.S.-based measurements, presuming a transition from Smithsonian 1913 to IPS 1956 at the beginning of 1959, and then described the NOAA Global Monitoring for Climatic Change program and plans.

Thekaekara pointed out that the NWS records of direct solar intensity show that recent values appear to be about 6 percent lower than those of 1950–54, probably due mostly to the change of scale in 1959 mentioned by Hanson.

TABLE D-I
Experiments Proposed for the NASA Program of Measuring the Total and Spectral Irradiance of the Sun from Spacecraft

Instrument	Proposed flight system	Measurement total spectrum	Accuracy (Goal)	Instrument Status[a]	Proposing and/or Cognizant Organization(s)
Earth Radiation Budget (ERB)	Nimbus-F/G	XX	<1%	A-Nimbus	NOAA/NASA
Solar and Earth Radiation Monitor (RCR/SERM)	Tiros-N	X—	~1%	P-OSIP	NOAA/CSU/ NASA
Active Cavity Radiometer (ACR)	ERBOS	X—	0.2–0.5%	F-SR & T	Univ. of Wis./ NASA
Primary Active Cavity Radiometer (PACRAD)	LZEEBE/ CLIMSAT	X—	0.2–0.5%	A	JPL/NASA
Eclectic Satellite Pyrheliometer (ESP)	AEM/Shuttle	XX	0.2%	F-AAFE	NASA
Solar Energy Monitor in Space (SEMIS)	LANDSAT/ Solar Max. Mission/ AEM/Shuttle	XX	0.5→0.1%	P	NASA
Total Solar Irradiance Measurements (TSIM)	Tiros-N	X—	0.1%	P	NOAA-ARL
Solar Constant and Spectral Distribution (SCSD)	TBD	XX	0.5%	P	Faraday Labs
Solar Irradiance Cavity Radiometer (SCIR)	CLIMSAT/ Shuttle	X	0.2%	P	NASA/NBS

[a] A—Available, F—Funded Study, P—Proposed Study

Thekaekara also presented a table listing various planned or proposed NASA projects connected with measuring solar radiation. (See Table D-I).

In the general discussion of what should be done, the consensus seemed to be:

(i) A cavity radiometer should be put in space as soon as possible, even though the degradation problem is not yet solved.

(i) Measure spectral irradiance over the largest possible range, with priority to the high energy region.

(iii) Measure spectral irradiance with increased absolute accuracy in the far UV.

(iv) Observations from space should be supplemented by ground-based observations. A chief function of observations from space should be the calibration of the (longer-term and much less expensive) ground-based measurements.

In the last talk of Session D, Wilcox discussed a correlation between weather phenomena and sector structure in the solar wind. There appears to be about a 10 percent decrease in the area of low pressure troughs in the northern hemisphere when a sector boundary moves past the Earth in the winter. Wilcox emphasized that the sector boundary should be considered mainly as a time marker rather than as necessarily the direct cause of the correlation. For example, the cause might be due in part to UV radiation from the Sun which also correlates with sector boundaries.

In the discussion after the talk, Wilcox stated that low-latitude coronal holes also correlate with sector structure. He also mentioned that there appears to be a 22-year drought cycle in the Western Plains States.

3.5. Session E: summary and general discussion of future observational programs

Chairman: O. R. White; *Rapporteurs*: G. Chapman and Ron Moore

In the first talk, J. D. Hays reviewed paleoclimatic variations and gave his opinions on the plausibility of these variations being caused by changes in the solar constant. He began by stressing the very long term uniformity of the climate implied by the strong geological evidence that there has been life on the Earth over the past 2–3 billion years. This indicates that the Earth was never completely frozen over. The models of Sellers and Budyko then imply that over the past 2–3 billion years the solar constant hasn't been more than about 5 percent less than it is now. For these reasons, Hays' strongest opinion was that there is a direct conflict between geological evidence and the theoretical evolution of the Sun which calls for about a 20 percent increase in the solar constant over the same time span.

In the last billion years there have been three relatively short (~10 million years) periods of glacial ice separated by much longer periods (~300 million years) of very little ice. The last of the three glacial periods includes the present. Hays' second opinion was that the three abnormal cold periods were probably not due to changes in the solar constant. He put forward positioning of continents at the poles by continental drift, changes in sea level and volcanic activity as more likely causes of such glacial periods.

Hay's third opinion was that the climate changes most plausibly connected with changes in the solar constant have time scales shorter than about 2500 years. Possible characteristic time scales are 2500, 400, 180, 80 and 22 years. He felt that changes of time scale 10^5 years were more likely due to changes in the eccentricity of the Earth's orbit rather than changes in the solar constant.

In the discussion following Hays' talk, Robinson pointed out that Hays' conclusion that the solar constant could not have been 5 percent less than at present during the past 2–3 billion years was based on the models of Sellers and Budyko which in turn are based on the present atmosphere. Sellers felt that the decrease in the solar constant of 5 or 10 percent (before the planet is ice covered) allowed by the climate models and the 20 percent decrease implied by stellar models may not be different enough to indicate a definite conflict between stellar evolution models and the geological evidence for life. Hall pointed out that even though Hays' arguments implied the solar constant could not have been much less than it is now, the same evidence does not rule out larger (>5%) past increases in the solar constant.

Hays and others emphasized that the 'normal' climate is that between the shorter cold periods, one of which we are now in. Another point brought out was that the advance and retreat of glacial ice during one of these cold periods may be controlled or paced by the changes in eccentricity of the Earth's orbit. It was also pointed out that the internal heat of the Earth probably does not affect climate except through volcanism. Smith mentioned that the past history of the Moon and its orbit may have influenced climate.

In the second talk, Eddy summarized the constraints placed on the variability of the solar constant by the observational evidence discussed during the conference. He listed the following observational results for limits on the variability.

(1) Abbott's data between about 1920 and 1950 suggest a variability of about ±0.1%. There are problems with these data such as the fact that rather large areas of sky were observed along with the solar disk, and the fact that atmosphere cut off the observed radiation shortward of 3000 Å and longward on 2.3 μ (5 or 6% of the total radiation).

(2) The summary of total irradiance measurements in the 1960's compiled by Labs and Neckel indicates a limit on the variability of about ±1%.

(3) Balloon measurements by Kondratyev and Nikolsky suggest a possible variation of ±1% in 1967.

(4) Lowell Observatory observations of the planets over the past 25 years allow a variation of ±0.5%.

(5) JPL spacecraft measurements possibly show 0.2% changes over an 18 month period in 1967–69.

Eddy therefore concluded that we can only say that the solar constant probably has not varied by more than ±1% in the last 50 years.

The following ideas were contributed in discussion during and after Eddy's talk. Brueckner made a plea that more careful and detailed calculations should be made of the modification of the solar spectrum by sunspots and plages from existing data on their spectra. Heath expressed his feeling that there may be a variation of solar radiation connected with the 11-year or 22-year magnetic cycle other than the radiation from sunspots and plages. Mitchell pointed out that 0.1% is the level at which variation in the solar constant becomes important in models of the weather and climate.

In the third talk, O. R. White reviewed the vertical temperature structure of the solar atmosphere, pointing out which parts of the solar spectrum are formed in each layer and the basic physical mechanisms operating in each layer. His main points were (1) that the temperature minimum layer above the photosphere is definitely modified (heated) in the magnetic active regions on the Sun, (2) that both the UV around 2000 Å and the IR around 100 μ are formed in the temperature minimum and (3) that the radiation in both of these wavelength regions is important in the energy balance and dynamics of the Earth's atmosphere.

In discussion following White's talk, Foukal, Quirk and Kaplan all emphasized that it is not known whether absorption of IR and UV by ozone or absorption of IR by water vapor is more important in the dynamics of the atmosphere. Roosen warned that it is not completely established that the bulk of the ozone is produced through photoionization absorption of UV in the atmosphere in the equatorial regions; bombardment by energetic particles in the polar regions may also produce a significant amount.

Next, a short talk was given by G. Brueckner on rocket and space observations of the solar UV around 1900 Å taken during the period 1968 to 1975. He concluded that there can be a variation in this flux of about 6% over a solar rotation and that there was less than 20% variation over the past solar cycle. He also reported that NRL has the capability of measuring the Schumann–Runge ozone absorption band and its variation with height in the atmosphere.

Another short presentation was given by G. Chapman of a new scheme, devised by Prag and Chapman of the Aerospace Corporation, for measuring the solar constant by a satellite. The key part of the scheme is the simultaneous measurement of the photon momentum and energy flux.

White, with the aid of several members of the audience, then listed the observational programs which will bear on the solar constant problem for the next few to several years.

(1) OSO-I, to be launched in June 1975, will study the 2300–1100 Å region and will have calibration rocket flights.

(2) In October 1979, the Solar Maximum Mission (SMM) satellite will hopefully be flown.

(3) Between OSO-I and SMM there will be the Aeronomy Explorer satellite, the Nimbus satellite, the Solrad-Hi satellite (Nov. 75) and various NRL rockets. Nimbus will have a radiometer, but not an absolute instrument, and Solrad-Hi and the rockets will measure the solar spectrum below 2000 Å.

(4) During 1975–76 KPNO will measure the solar spectrum in the yellow and blue, and in particular will be studying line depths. KPNO will also work in the 10–15 μ region.

(5) GSFC will have radiometers at Mt Laguna, California and at Mt South Baldy, New Mexico. The intent is to measure changes in the solar flux, not the absolute flux.

(6) BBSO and JPL plan to collaborate in radiometer measurements. (Willson said that his radiometer with a spectrometer would cost about $K 10.)

(7) JPL plans radiometer measurements on balloon flights, 4/year beginning in fall of 1975 and continuing for one year.

(8) NOAA will measure the solar intensity at the ground using 5 view radiometers at four stations.

Zirin then read a proposed 'statement of the Solar Constant Workshop' to be sent to the GARP Committee, and the purpose, content and wording of the statement were discussed.

The remainder of the session consisted of a discussion of the support and operation of a long-term solar constant measuring and monitoring program. The main point to come out of this discussion was that solar constant measuring programs should be carried out for a minimum of 11 years, but that there is little chance of long-term funding from the government. Peacock stated that NSF would not support long-term observations just for the sake of data collecting; a strong personality would have to be running the program and be interested in analyzing the data. Roosen and Robinson concurred that a strong personality would be necessary even to carry out a long-term program. Peacock suggested a collaboration of spacecraft mission funding by NASA, ground-based instrument funding by NSF and long-term observation funding by NOAA. Timothy envisioned rather short-term funding by NASA mainly for space observations to calibrate ground-based observations. It was also agreed that the sampling rate during even a long-term program should be daily for both solar constant and spectral irradiance measurements. Finally it was emphasized that these measurements should be started as soon as possible.

Appendix I. Program

SESSION A. THE SOLAR BACKGROUND

Chairman: Harold Zirin (California Institute of Technology)
Rapporteurs: Peter Foukal and William Adams

*1. Roger Ulrich (University of California, Los Angeles): 'Solar Neutrinos and Variations in the Solar Luminosity'
*2. Jack Eddy (High Altitude Observatory): 'The Last 500 Years of the Sun'

* An asterisk indicates contributed papers for which manuscripts were received (all included in BBSO No. 0149).

*3. Peter Foukal (Harvard College Observatory): 'The Contribution of Active Regions to Solar Variation in the Visible and Near Infrared'
*4. G. W. Lockwood (Lowell Observatory): 'Evidence for Solar Variability from Photometry of Planets and Satellites'
5. J. B. Oke (California Institute of Technology): 'Absolute Measurements of Stellar Radiation: Can They be Tied to the Sun?
*6. G. E. Brueckner, J.-D. F. Bartoe, O. Kjeldseth Moe, and M. E. van Hoosier (Naval Research Laboratory): 'Absolute Solar Intensities 1750 Å–2100 Å and Their Variations With Solar Activity'
7. Donald Heath (NASA/Goddard Space Flight Center): 'Space Observations of the Variability of Solar Irradiance'
*8. M. P. Thekaekara (NASA/Goddard Space Flight Center): 'The Total and Spectral Solar Irradiance and its Possible Variations'
9. Adrienne Timothy (NASA Headquarters): 'What Can the Solar Maximum Mission Do?'

SESSION B. THE CLIMATE RECORD BACKGROUND

Chairman: James Hays (Lamont Doherty Geological Observatory)
Rapporteurs: J. Murray Mitchell and Gordon Hurford

1. J. Murray Mitchell (NOAA Environmental Data Service) 'Problems of the Climate and Solar Variations'
*2. V. C. LaMarche (Laboratory of Tree Ring Research): 'Notes on Postglacial Climatic Changes and Possible Evidence for Long-Period Variations in the Solar Constant'
3. S. Epstein (California Institute of Technology): 'Measurement of Historic and Paleoclimate by Isotope Techniques'
4. James Hays (Lamont Doherty Geological Observatory): 'Summary of Paleoclimate Cycles and General Discussion'

SESSION C. MEASURING THE SOLAR CONSTANT

Chairman: Keith Pierce (Kitt Peak National Observatory)
Rapporteurs: O. R. White and Barry LaBonte

*1. D. Labs (Landessternwarte Heidelberg-Königstuhl Observatory): 'The Solar Constant and Its Measurement (From an Astrophysicist's View)'
*2. H. Neckel (Hamburger Sternwarte Observatory): 'On the Accuracy of Solar Radiation Measurements and the Need for Consistency of all Radiation Data'
*3. Glenn Shaw (University of Alaska - Geophysical Institute): 'Solar Spectral Irradiance - The Role of Earth-Based Measurements'

*4. G. Robinson (Center for the Environment and Man): 'Estimates of Solar Irradiance in the Region of Atmospheric Absorption Bands'
*5. C. Fröhlich and R. W. Brusa (World Radiation Center, Davos): 'Measurement of the Solar Constant: A Critical Review'
*6. R. C. Willson (Jet Propulsion Laboratory): 'JPL Absolute Radiometry and Solar Constant Measurements'
*7. L. Dunkelman (NASA/GSFC): 'Solar Spectral Irradiance and Atmospheric Extinction λ3000 Å to λ7000 Å: Mt Lemmon, Arizona Measurements in 1951 and Plans for Period 1975–76'
*8. J. Kendall (Jet Propulsion Laboratory): 'Measurements of Stefan-Boltzmann Constant, Circumsolar Irradiance, & the Solar Constant Made with PAC-RAD Radiometer'

SESSION D. WHAT HAPPENS TO THE ATMOSPHERE?

Chairman: J. Murray Mitchell (NOAA)
Rapporteurs: G. Robinson and Ron Moore

*1. F. Haurwitz (RAND Corportion): 'The Effect of Reducing the Solar Constant in a Climate Model'
*2. W. D. Sellers (University of Arizona): 'The Effect of Solar Constant Variation on Climate Modelling
*3. L. Kaplan (University of Chicago): 'Weather and Ozone, and the Solar Ultraviolet'
4. V. Suomi (University of Wisconsin): 'Heat Balance Problems'
*5. C. Leith (NCAR): 'Climate and General Circulation Studies at NCAR'
*6. J. M. Wilcox, L. Svalgaard, and P. H. Scherrer (Stanford): 'Sector Structure and Weather Phenomena'

SESSION E. SUMMARY AND GENERAL DISCUSSION OF FUTURE OBSERVATIONAL PROGRAMS

Chairman: O. R. White (HAO)
Rapporteurs: G. Chapman and Ron Moore

1. J. Hays (Lamont Doherty Geological Observatory): 'Summary of Paleoclimatic Variations and Their Possible Causes'
2. J. Eddy (High Altitude Observatory): 'Summary of the Possible Variability in the Solar Constant Allowed by the Observations'
*3. O. White (High Altitude Observatory): 'Comments on the Solar Spectrum and the possible Origins of its Variability'

4. G. Brueckner (Naval Research Laboratory): 'Observations of the Solar UV Around 1900 Å Over the Past Solar Cycle'
5. G. Chapman (Aerospace Corporation): 'A New Scheme for Measuring the Solar Constant'
6. Future Observational Programs.

Appendix II. List of Participants at Solar Constant Workshop

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