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VARIATIONS IN THE SOLAR CONSTANT

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Summary. In this review, using the latest results, an attempt is done to address the main problems of solar irradiance variability. Pointing out the difficulties of measurements and the weakness of theory the empirical results are analyzed as short-term variations, correlation with activity cycles and possible long-term changes in the solar constant.

M. Karabin. Dat je pregled glavnih problema promene Sunčeve iradijacije. Korišćeni su najnoviji rezultati.

1. INTRODUCTION

The problem of variability of the solar luminosity L[1], i.e. of variability of the solar constant C[2] is at least one hundred years old. Its importance is, among others, also due to the influence on Earth's climate and to the

[1] the solar luminosity L is the integral of the flux of solar radiation taken over the entire solid angle and all frequencies

[2] the solar constant C is the flux of the Sun being determined empirically, falling down to unit area at a distance of $1AU$, i.e. to the outer boundary of Earth's atmosphere $C[Wm^{-2}]$

possibility of analyzing the phenomena on the Sun and similar stars. The problem has been subject of analyzes done by many astronomers, among them also by Milutin Milanković as early as at the beginning of the present century. Here is quotation from his paper written in 1913.

"Our climate is doubtless of a female nature. However, despite all its "whims" historical data indicate that Earth's mean climate has not changed after many centuries. The reason that Earth's insolation has not been solved until my era has been neither in meteorology, nor in celestial mechanics, but it rather concerns the fact that the intensity of solar radiation has not been measured duly by 1913. Therefore, the number called the solar constant is not precisely known. Its determination has been attmepted by many observers since a long time, but their results differs very much."

The delay in solving the problem until nowdays has been due to the same reason. Although the registration of the solar constant began as early as in 1881. at the Smithsonian Observatory (USA) and towards the end of the XIX century at other places, frequent interruptions caused by improvements in the measuring methods and technics did not allow longer series. As late as in the last decade exceedingly qualitative long series of ground based measurements have been obtained (Foukal and Vernazza, 1979).

Extraordinarily small variation in amplitudes were found (0.1-0.3%) and by 1977 the error, even for the best results of solar constant measurements, was of the order of 10%. On account of this, absolute measuring of the solar constant had to wait until the satellite era, more precisely until 1979. Very sensitive radiometers on board of the spacecrafts: Skylab, OSO-8, NIMBUS-7, Solar Maximum Mission (SMM), IUE, HEAO-2 ("Einstein"), as well as Spacelab 1,2, made possible obtaining the first, really accurate, data on solar irradiance for the period from maximum (1979) to the minimum (1986) of the 21. cycle of the solar activity.

We want here to emphasize some problems present in the case of the satellite measurements in order to realize that the absolute determination of the solar flux both within limited parts of the spectrum, as well as that of the total solar constant, is not a trivial task of modern metrology. The measurements are carried out in short intervals, separated in time, when the satellite is in the direction of the Sun. For example, Spacelab 1 performed all its measurements of solar irradiance in four periods, between December 5 and December 8, 1983 with the total duration of 7 hours being less than 3% of the duration of its effective flight which lasted 247 hours. In the course of the measurements permanent comparisons are necessary since the solar radiation heats, damages and degrades the sensitive radiometers. The most recent measurements in the UV domain have an error of +5% (Labs et al., 1987). The fact is that the contribution of this part of spectrum in the total solar constant is small, but the error in the other parts of the spectrum is not less than 0.17-0.12% (Crommelynck et al., 1987). Finally, for the purpose of establishing long-term variations it is inevitable to use results obtained on board of miscellaneous spacecrafts in different years and consequently the data becoming inhomogeneous.

Because of all this mentioned above the following value is nowadays used for the solar constant

$C = 1361.5 + 2.5 Wm^{-2}\{error + 0.18\%\}$ [Crommelynck et al., 1987].

One should be especially cautious when interpreting variations in the solar constant whose amplitudes are so close to the error limits.

The vast theoretical and empirical material published recently we shall try to systematize in such a way that at first the physical factors which might change the Sun's luminosity will be presented, and afterwards follows the presentation of the empirical results which are classified according to their time scale.

2. PHYSICAL REASONS FOR VARIATIONS IN THE SOLAR LUMINOSITY

The radiation, i.e. the photon flux (F) is the dominant form in which the Sun emits its energy. This flux mostly determines the solar luminosity. A very small fraction of the energy has been transported into the upper layers heating in this way the chromosphere and the corona to high temperatures and consequently producing a number of MHD phenomena. Although they receive energy in a nonradiative form, both the chromosphere and the corona emit energy in the radiative form (X, UV, H_α, radio). The outer corona alone emits a part of its energy as a flux of charged particles: the global emission is known as the solar wind and the local one is producee at places of open magnetic fields (coronal holes). This particle flux cannot be compared in the global scale with the radiative one which prevails (Athay, 1986).

The bolometric luminosity of the Sun (L) is by definition determined by the radiative flux

$$L = \int_{4\pi} \int_0^\infty F(\theta, \nu) d\omega d\nu, \tag{1}$$

where ω is solid angle and ν is the frequency. It depends on the change in the efficacy of the energy transfer from the interior towards the photosphere.

Only those luminosity variations whose time scale is less than 10 years will be analyzed here since in the case of longer time scales reliable data are missing.

The models used in the study of the solar atmosphere are much more reliable than those applied to the solar interior. In order to study the energy transfer towards the photosphere theoretical models containing the following assumptions are used

a) the hydrostatic equilibrium

$$\frac{dp}{dr} = -\rho g = -\rho \frac{GM}{r^2}, \tag{2}$$

b) the radiative equilibrium with the Planck type of radiation

$$-L_r = 4\pi r^2 \sigma T^4, \tag{3}$$

c) a homogenous internal structure,
d) the star does not rotate and it possesses no magnetic field.
In such models the energy transfer takes place either by radiation,

$$F_r = -\frac{4ac}{3}\frac{T^3}{k\rho}\frac{dT}{dr}, \tag{4}$$

where $k = k(r,\rho,T)$ is the opacity coefficient; or by convection in situations when the opacity increases rapidly with depth so that a large temperature gradient arises. In the case of convection the temperature fluctuations are determined by means of the well-known Schwarzschild criterion

$$\Delta T \sim |\frac{dT}{dr}|_{real} - |\frac{dT}{dr}|_{ad}. \tag{5}$$

Whereas hot stars possess a convective core, those cooler than the spectral type F5 possess convective atmospheres, i.e. a convective zone exists in them. As the effective temperature decreases, the thickness of the convection zone increases. In the case of the Sun it is about 30% $R_\odot$ (Gilman, 1986).

In order to analize the energy transfer through the convection zone one uses the well-known "mixing-length" approximation (Bohm-Vitense, 1953) in which the characteristics of the convective elements at the given depth are determined by only one parameter: $\alpha = \frac{l}{H}$, where l is so-called mixing lenth, the path passed by a convective element before exchanging with the surrounding medium the energy and the momentum carried by itself. The quantity H, $H = \frac{dr}{d\ln P}$, is the pressure height scale. To a certain model α is a constant parameter.

Using this approximation and neglecting the friction one can write the following expression for the flux transfered by convective elements

$$F_c = \frac{C_p\rho}{2H} g^{\frac{1}{2}} T^{\frac{3}{2}} \alpha [(\frac{d\ln T}{d\ln p})_{real} - (\frac{d\ln T}{d\ln p})_{ad}]. \tag{6}$$

From (6) it is evident that the amount of the parameter α affects directly the efficacy of the convective transfer which determines the luminosity. Unfortunately, an adequate theory of internal structure of stars is still lacking. Not only that there are a number of limiting approximations and idealizations given a priori, such as a)–d), but some essential parameters have not been precisely determined yet. For example, various models have assumed different values for α ($0.5 < \alpha < 3.0$); Gough and Weiss, 1976; Gilman, 1986). The values of H and k are also uncertain (Zahn, 1981).

Much is expected from absolute measurements of the solar luminosity and its variations, since they will make possible corrections in the models, i.e. a more precise determination of the relevant parameters. No doubt, the magnetic field generated by a convective large-scale turbulence within a star must modify the eficacy of the convective transfer, but at present there is no corresponding theory. Only partial solutions have been looked for (Roxburg, 1981).

It was supposed as early as in 1941 by Biermann that the lower brightness and the temperature within a sunspot arise because of the concentration of magnetic force lines which reduce, i.e. block the convective energy transfer. The influence of a magnetic field limited in space on the inhibition of convection was analyzed by Wilson (1968), Gough and Weiss (1976), etc, but even at present there is no model yielding a quantitative relation

$$L = f(R, T, B), \tag{7}$$

though the influences of variations in the radius, temperature and magnetic field on the luminosity are evident. The depth (d) at which the sunspots appear is also unknown. Various values have been used in models of different theoreticians (Newkirk, 1983):

$$700km < d < 120000km.$$

A numerical analysis of a "standard" sunspot model indicates that it is to expect the solar constant to be diminished by the amount

$$(C_s - 1)A_s, \tag{8}$$

where is C_s – contrast factor of the sunspot brightness to the one of the photospheric continuum; A_s – projected sunspot area.

A problem of "missing energy" has appeared. An energy of the order of 10^{36} erg cannot reach the level of sunspots because of magnetic field blocking. If the missing flux got around the obstacle (a sunspot), a bright ring surrounding the sunspot would appear. However, such a phenomenon has not been registered! This problem has given an impetus to a number of papers characterized by different ideas, indeed. Among them one should especially point out Parker's (1974) paper which, though has been significantly modified (Cowling, 1976; Parker, 1978, 1981; Spruit, 1982), has preserved its basic idea. Thus it is thougth today that only a smaller part of the blocked flux is irradiated immediately in the vicinity of a sunspot through bright faculae, whereas a larger part is transformed within the sunspot into the energy of MHD waves. The waves are reflected and returned to the convective zone as an internal potential energy. This part of energy is trapped and it cannot return to the surface in shorter than a month.

It has not been easy to give an observational confirmation of Parker's idea since it is extremely difficult at the place of a sunspot to measure velocities and to determine the sense of the plasma motion (the Evershed effect, oscillations).

Let us see what has been obtained from measurements.

3. EMPIRICAL RESULTS AND DISCUSSION

Variations in the luminosity (L) can arise, as it has been shown above, because of variations in the radius (R), or due to variations in the efficacy of the convective transfer (T,B). However, since theory can still give no explicit solution of (7), or in other words it can give no model yielding quantitative values of L as a function of variations in the basic parameters R, T and B, any reliable measurements become very important.

Many investigators have attempted to verify correctness of Parker's idea from 1974 by comparing it to the results of their own measurements. It is of interest to mention the papers written by Yugoslav astronomers . A. Kubičela (1973) determined the vertical velocities at the boundaries of supergranular cells. According to P. Ranzinger (Bumba et al., 1973) the sunspots appear in quantums just within the scales of supergranular cells. The relationship between the sunspots and supergranular cells is not clear yet (Frazier and Stenflo, 1978; Bumba, 1987). It is believed that the correctness of Parker's idea was confirmed by Giovanelli and Slaughter in 1978 by measuring velocities of photospheric downward motions up to the value of 0.6 $km\ s^{-1}$ at the places of concentrated magnetic flux (boundaries of SG cells and sunspots). This result may be considered statistically as a resultant taken over all plasma motions at those places. The most recent result of this kind was obtained by measuring velocities of downward motions at the places of sunspots, at the levels of the photosphere ($v \approx 0.3kms^{-1}$) and of the chromosphere ($v \approx 1kms^{-1}$) (Gopasyuk, 1987). So, for the moment, the missing flux problem seems to be solved. Before discussing the results of the solar constant measurements (divided here into three groups according to the time scale of the variations), a short review of the solar radius measurements will be presented.

3.1 Variations in the Solar Radius

The radius of the Sun (R) is a directly measurable quantity which is of interest to many problems of solar physics. For the present purpose it is important because of the direct influence of posible variation in R on the solar luminosity according to (3):

$$\frac{\Delta L}{L} = \left(\frac{\Delta R}{R}\right)^2 \left(\frac{\Delta T}{T}\right)^4 \approx 0.2\%. \qquad (9)$$

It is evident that the variations in the solar radius, if they exist at all, are very small. This is the reason for contradictory results obtained by many investigators till now. Some of the recent ones are: Eddy and Boornazian, 1979; Sofia et al., 1979;Gilliland, 1981, 1986; Delache et al., 1985; Ribes et al., 1987; Morrison et al., 1988.

In view of such a situation accurate everyday measurements of the solar radius have been recently initiated at a few observatories. Measurements of this kind have been done at the High Altitude Observatory (USA) with an accuracy of 0."4. In the period between 1981 and 1986 no radius variations within the error limits were found (Sivaraman, 1985; Gilliland, 1986). It is obvious that the measurements must become more accurate and to answer this question reliably one need longer time series. Until these requirements are satisfied, variations in the solar luminosity will be looked for in the change of the convection efficacy assuming that

$$\Delta R = 0. \tag{10}$$

3.2 Short-term Variations in the Solar Constant ($day < t < week$)

The solar constant is a quantity which can be subjected either to ground-based measurements or to satellite ones. The question of to what degree the solar constant, itself, is an indicator of the solar luminosity is a question of the radial structure of the solar irradiance, i.e. of the structure of the solar atmosphere. At present this question cannot be answered definitely, but the spherical-simmetry approximation is thought to be fully justified when the photosphere (its irradiance) is concerned and that its application becomes progressively deteriorated from the photosphere towards the corona.

The first proof that the sunspots change the solar constant was obtained by Foukal and Vernazza (1979) not by using any satellite measurements, but by analyzing a long series of ground-based measurements (1923-1952). This result was confirmed shortly afterwards by measurements done beyond the terrestrial atmosphere aboard the satellite SMM/ACRIM (Willson et al., 1981). During the transit of a sunspot group through the central meridian (CM) of the solar disc fallings of short duration in the solar constant most frequently by about 0.1% (exceptionaly reaching even 0.25%) have been determined as the mean value of the C measurements reduced to the geocentric distance of the Sun of 1 A U.

A similar result has been obtained from the measurements of the satellite NIMBUS/EBR (Foukal et al., 1981).

These first proofs of diminishing in the solar irradiance due to the sunspots confirm the theoretical predictions and at the same time the small values which have been measured explain why one has waited so long to obtain a confirmation of Biermann's idea from 1941. For the missing flux, as well as the role of faculae in its compesating, one may say that there are almost as many different results as there are authors. However, at one point all of them agree: Significant part of the flux remaines blocked somewhere within the convective zone and a smaller one is compensated through an enhanced emission of faculae. The author disagree concerning the estimate of the global participation of faculae in the energy balance whose result is measured as the solar constant (Newkirk, 1983; Chiang and Foukal, 1985; Chapman and Meyer, 1986). In our opinion this problem cannot be solved at the present level of theory and measurements. It is interesting to note that the variations in the integrated flux found for other stars whose spectral type is F–K and rotation period is between 11^d and 48^d have the same variation rate as obtained for the Sun

$$\frac{\Delta F}{F} \approx \frac{\Delta C}{C} = (0.1 - 0.2)\%. \quad (11)$$

Exceptions are fast–rotating double stars of the RS CVn and BY Dra type whose integrated flux variations are so large that their "spots" probably cover about 30% of the visible disc unlike the sunspots which cover only 5–6%. This result indicates a higher level of magnetic activity for those stars (for the details see Vukićević–Karabin and Arsenijević , 1986).

3.3 Variations in the Solar Constant during a Solar Activity Cycle ($t \approx 11 years$)

When the influence of the sunspots on the solar constant variations was confirmed (Foukal and Vernazza, 1979, 1981; Willson, 1981, 1982), a new question arose–the question on the influence of the whole activity cycle. Results of accurate, absolute, solar constant measurements covering a whole cycle are not available yet and to answer it one should wait a few years. Instead of waiting astronomers have tried to analyze the archiv data on measured sunspot areas concerning the period between April 1874 and October 1981. The variations in the solar constant during last ten cycles were calculated on the basis of such data (*Fig.*1) (Newkirk, 1983). Though one should be very cautious in interpreting these data, especialy those corresponding to earlier epochs, it is seen that the obtained variation of the solar constant is periodic and that the minima coincide with the cycle maxima, as could be expected.

Much more reliable are the satellite measurements covering the period 1981–1985, particularly taking into account that this is the first long series of reliable, accurate, direct, measurements corresponding to a semi–period between a maximum and a minimum of the solar activity. A quite unexpected result, not explicable at present, was obtained. Instead of expected increase in the solar irradiance during a declining activity phase, the measured values indicated a steady decrease for the examined period. Since one cannot explain the latter result by the influence of the activity cycle, it will be the subject of a special discusion in section 3.4.

At this place, since the total solar irradiance and its variations during an activity cycle are analyzed, one should certainly draw attention to a fact overlooked by some authors. Some lines in the solar spectrum have shown variations in their characteristics (equivalent width, depth) just folowing the rhythm of the solar cycle variations. Thus one can use them as indices of the solar cycle. The best example is the flux of the Ca II K line taken over the entire solar disc. The fact was noticed as early as in 1967 by Bumba and Topolova and it has been confirmed by many other investigators by using long measurement series later on (Bappu and Sivaraman, 1977; White and Livingston, 1978; Keil and Worden, 1984). It has been found out that such a Ca II K flux emmited from the entire disc is very convenient to study the solar activity (max/min 15%) and it has been also used for the purpose of studying the stellar activity. Variations greater than the latter ones have been found within the UV and X domains of the spectrum from the satellite measurements. The greatest variations during the solar cycle occur in the two extreme parts of the spectrum (X and radio). Their amouns are $10 \leq max/min \leq 10^3$ and they are important for these parts of the spectrum. However, their contribution to the total solar constant is not measurable at present (*Fig.*2) because the participation of all lines at wavelengths shorter than 300 nm and longer than 1 mm is less than 10^{-6} (Rutten and Cram, 1981).

3.4 Long–term Variations in the Solar Constant t=?

A monotonous decrease in the quantity $\Delta C/C$ whose annual amount is $0.17 \pm 0.003\%$ was established from measurements with precise radiometers carried out beyond the terrestrial atmosphere between 1981 and 1985 (Hickey, 1985; Willson et al., 1986; Foukal and Lean, 1988). This result unexpected for declining phase in the solar activity (*Figs.* 3 *and* 4) caused a real sensation and confusions which still last. Modern climatology has demonstrated that a secular variation of 0.5% in the solar constant would cause drastic changes in Earth's climate. The measured deacrise in the solar constant is very large if its duration is long enough. In a century it would attain 2%! It is really unknown to us how long this phase will last and what is more important, we do not know whether the phenomenon is real or apparent.

There is an independent result indicating reallity of the phenomenon. Since 1976 a research team from the Kitt Peak Observatory (Livingston and Holweger, 1982) has been studying the influence of the activity cycle on a large number of spectral lines measured over the entire solar disc. One of them, a carbon line (CI 538.0 nm) being formed deep within the photosphere, has not shown any variations in its characteristics following the rhythm of the solar activity. Therefore, before the result concerning a possible long–term photosphere cooling was obtained, this carbon line had been quite uninteresting. From the begining of measurements in 1976 till 1985 its equivalent width and depth were steady changing. These changes could be attributed to an effective temperature decrease whose annual amount should be equal to $\sim 2.6K$ on the basis of the variations established in the equivalent width, i.e. to $0.7K$ on the basis of ones found in the depth.

If the decrease $\frac{\Delta C}{C} = (0.017 \pm 0.003)\%$ is due to a temperature change, then one obtains (assuming $\Delta R = 0$) fpr the annual cooling of the photosphere a value of about 1.3 K. The latter result is in a quantitative agreement with the variations in the spectral line C I 538.0 nm(Gilliland, 1986).

The agreement between the two results is still not enough to explain either the cause or the nature of the observed phenomenon, but it indicates

a) that the measured effect of the long–term decrease in the solar constant might be real;

b) that the photosphere most likely possesses a slowly varying component whose time scale is still unknown, but for which the neither the number nor the area of the sunspots are appropriate indices.

4. CONCLUSION

Our knowledge about the solar irradiance has been changed significantly during the last ten years due to results of the first reliable measurements carried out beyond the terrestrial atmosphere in long series.

Short-term variations visible as dips in the recorded data are due to the sunspot blocking of convection by magnetic field. The storage and redistribution of the missing flux is still an open question.

The question about the influence of activity cycles on the solar irradiance has to wait for further measurements. At present an indication of possible variations in the solar constant (max/min $\approx 0.1\%$) has been obtained from the archive data for the period 1874–1981.

A long–term decrease in the solar irradiance may be related to global changes in the photospheric temperature, as recent experimental results have not confirmed any significant variations in the solar diameter. A special attention has been drawn to the deep photospheric line CI 538.0 nm whose depth and equivalent width show no variations vith the activity but indicate a long- -term decrease in the effective temperature.

New results of accurate, absolute, measurements of the solar bolometric irradiance are expected also as a valuable aid for understanding the interaction of the solar magnetic field with plasma motions and heat transfer. These questions are still waiting for answers by solar physicists.

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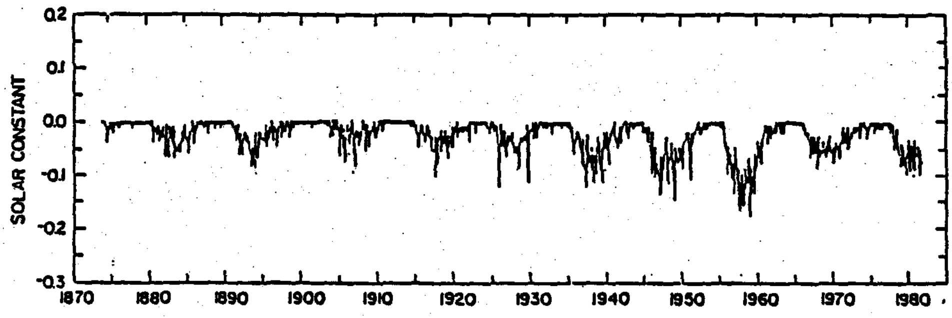

Fig. 1: The monthly mean values (%) of the solar irradiance from April 1874 till October 1981 reconstructed from archived sunspot area (from Newkirk, 1983).

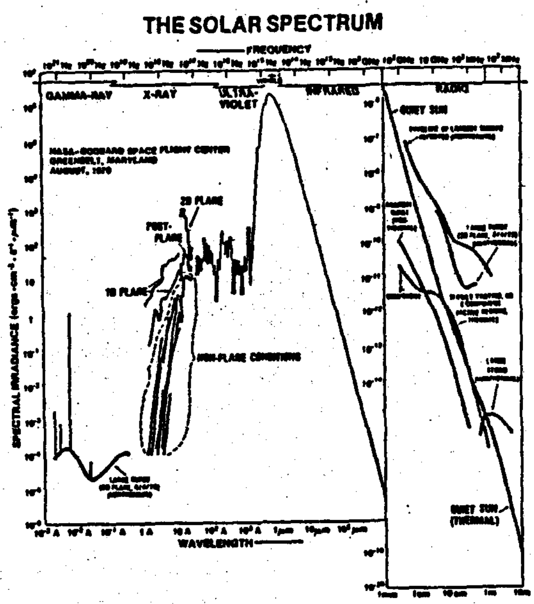

Fig. 2: The quiet Sun and active components of solar irradiance spectrum (from Rutten and Cram, 1981)

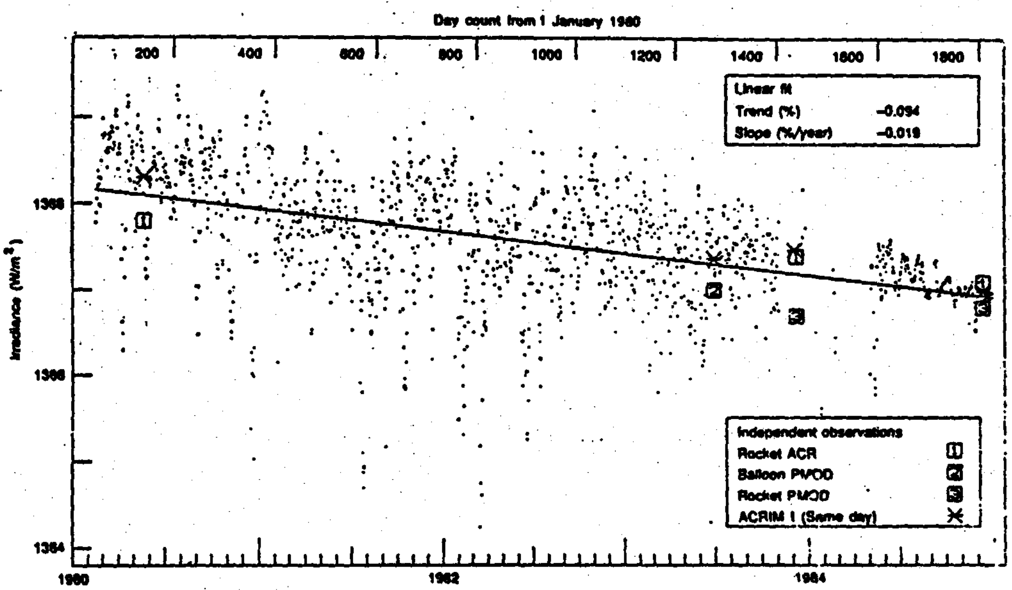

Fig. 3: Total solar irradiance at $1AU$ obtained by SMM/ACRIM, rockets and balloons (from Willson et al., 1986).

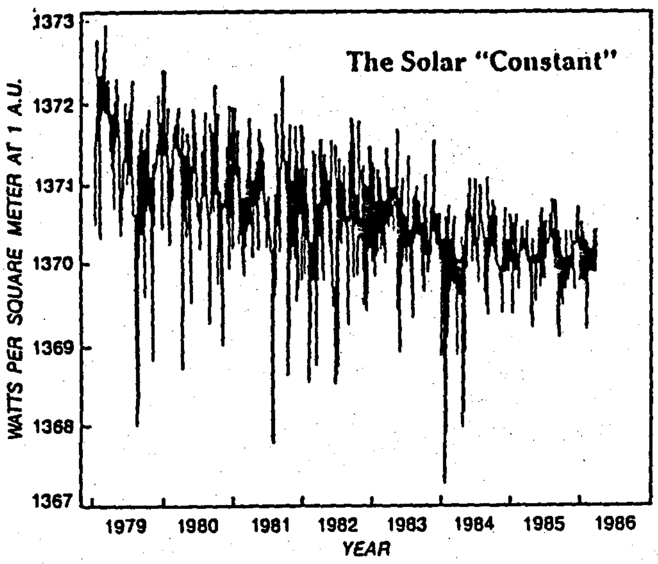

Fig. 4: Downward trend in solar irradiance at $1AU$ obtained by NIMBUS–7/ERB (from Foukal and Lean, 1988).

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