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The solar cycle variation of the solar wind helium abundance

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Abstract

This paper is concerned with a critical survey of the experimental evidence for a variation of the relative abundance by number h, ($n\alpha/np$), of Helium in the solar wind. The abundance is found to vary by $\Delta h = 0.01 \pm 0.01$ from 0.035 to 0.045 over solar cycle 20. The change in the average bulk speed during the solar activity cycle was insufficient to account for this increase in $\langle h \rangle$ with the solar cycle. The slope of the linear relation between h and the plasma bulk speed is also found to vary, being greatest around solar maximum. An attempt is made to explain the 30% variation in $\langle h \rangle$ as the result of the variation in the number of major solar flares over a solar cycle. These obvious transients are apparently not numerous enough to explain the observed variation, but the reasonable expectation remains that the transients observed recently by Skylab which may occur more frequently than major flares could augment those associated with major flares. Since the solar wind flux is not observed to increase at solar maximum, the abundance of Helium cannot be proportional to the proton flux leaving the sun unless the solar wind comes from a smaller area of the sun at maximum than at minimum.

INTRODUCTION

One of the most remarkable facts concerning the observations of lium in the solar wind is the wide variation of the helium to hydrogen ratio, i.e. from undetectable levels to greater than 25% (for a review see Bame, 1972). Although a great deal of study, some theoretical and some empirical, has gone into the problem, the causes of most of the variations are not understood. Among the variations that may have the most basic relevance to an understanding of the interaction of the helium and hydrogen plasma is the possible solar cycle variation of the helium abundance (Robbins et al. 1970, Bame 1972). It has long been proposed that such a solar cycle variation exists, and may be almost as large as a factor of two (c.f. Bollea et al. 1972). The question of the reality, size and cause of this solar cycle variation becomes of more interest when we consider that the solar cycle variation of other quantities in the solar wind are either small or extremely difficult to measure (Gosling et al. 1971, Montgomery et al. 1972, Diodato et al. 1974). In addition, it has been argued (Hirshberg 1973) that, if the apparent increase of He/H with the solar cycle is real, then the solar corona can not be completely mixed.

In this paper we examine carefully the data on the solar wind helium abundance in order to better estimate the size of the solar cycle variation of the helium abundance, and discuss some possible causes of the effect.

1 - SOLAR CYCLE VARIATION OF THE PROTON COMPONENT OF THE SOLAR WIND

Before observations were made of the solar wind itself, it was widely believed that it would exhibit a strong solar cycle dependence. This was based on at least three independent observations; first, the dramatic changes in the appearance of the solar corona with the solar cycle, second, the well established solar cycle variation of geomagnetic activity, and third, the solar cycle variation of galactic cosmic rays. It was therefore reasonable to expect that some dramatic changes would also appear in the solar wind as the solar cycle progressed. However, this has apparently not occurred and those changes that have occurred have been more subtle than dramatic. For example, Hirshberg (1969) compared the magnitude of the interplanetary magnetic field measured in 1963-1964 (Ness et al. 1966), with that measured in the same months of the year during the rising part of the solar cycle, i.e., 1966-1967. The distributions were remarkably similar, each having 75% of the values between 3γ and 8γ. The major difference in the two distributions was a "tail" which appeared on the distribution of magnetic field magnitude during the period of increased solar activity, apparently caused by intense fields associated with solar flare disturbances. Schatten (1971) extended this study to 1968 with comparable results. It has also been noted (Hirshberg 1973) that there is about a 25% variation in the modal value of the interplanetary field intensity during the period from 1963 to 1969 which is in phase with the solar cycle variation of geomagnetic disturbances for the same period. In evaluating these results it should be kept in mind that the recent solar cycle has been a very small one as measured by many of the usual indicators.

No clear and dramatic variation has been noted in the properties of the protons as the solar wind cycle has progressed. Gosling et al. (1971) have shown that the yearly mean velocity did not change by more than 50 km per second from 1962 to 1970. Hirshberg (1973) contends that if the same data were divided into years of high versus low geomagnetic activity, it appears that the distributions of velocity are distinctly different, the modal value for low activity being 325 km/sec (average velocity 409) and for high activity 425 (average velocity 472). The justification for using geomagnetics as the indication of phase of the solar cycle variation of the solar wind rather than the smoothed sunspot number, is the notion that geomagnetic activity reacts to the solar wind in the vicinity of the earth. The sunspot number is much more loosely connected to solar wind variation, both because the smoothed sunspot number is measured from the entire sun and also, more importantly, because the solar wind does not come from sunspots, but from some other coronal feature, the solar cycle variation of which may not be in phase with the sunspot number. A simple example of a measure of the solar cycle that is out of phase with the sunspot number is the average number of sunspots within 15° of the solar equator. However, no matter what the phase of the solar cycle variation of the solar wind may be, there is no doubt that the effects on the velocity are subtle, if they are real at all.

Other parameters have been studied, more or less extensively. For example, it has been noted that there is an apparent proton density decrease between 1964 and 1970 (Montgomery et al. 1972, Diodato et al. 1974). In determining the magnitude of this decrease ($\sim$ 40%) Diodato et al. 1974 have attempted to remove instrumental effects by cross calibration. Although Diodato et al. 1974 present some evidence to the contrary, there is possibly (Hundhausen et al. 1971) a heliographic variation in density and velocity. This complicates matters somewhat since the position of the spacecraft was not taken into account in producing most of the histograms used in the studies of the solar cycle variations of the plasma properties. An exception to this was made in the case of the magnetic field intensity (Hirshberg 1973) where data from the same months in each year were used as far as possible.

A discussion of the observation of the solar cycle variation of the helium abundance is the main subject of this paper and will be delayed until section 3 of the paper.

2 - VARIATIONS OF He/H ON THE TIME SCALE OF SOLAR ROTATIONS OR LESS

One of our tasks will be to re-evaluate the accuracies of the determination of the helium abundances made by the various plasma probes. This becomes possible because we have acquired a good deal of empirical knowledge about the variations of helium, which can be used to estimate systematic errors that may have arisen in each of the experiments.

The problem of determining solar cycle changes in the relative abundance of helium by number, $h = \frac{n_\alpha}{n_p}$, is complicated by the variability of h on shorter time scales. This variability would not cause difficulty in the determination of the average helium abundance $\langle h \rangle$, if the variations were random. However, they are not (Ogilvie and Wilkinson 1968). The value of h often remains far from $\langle h \rangle$ for periods of the order of hours or days, as illustrated by Bame (1972). Robbins et al. (1970) averaged values of h from Vela 3 over 10 day periods and found that $\langle h \rangle$ varied from less than 2% to greater than 8%. This variation was not simply due to sampling as can be seen in figure 1, which shows 3 hour averages of Vela 3 data for two 27 day periods.

Empirical studies of the variations of h have been carried out, and the following conclusions have been drawn; the value of h is correlated positively with the velocity u, there is a weak negative correlation with proton density, and essentially no correlation with either proton or α particle temperature (Robbins et al. 1970). Major enhancements of the helium abundance ($\geq$ 15%) are associated with disturbances caused by major flares (Hirshberg et al. 1970), many of which produced solar proton enhancements. Quantitatively, it has been shown that the helium abundance increases linearly with the velocity (Hirshberg et al. 1972; Bollea et al. 1972) and that the constants of the least squares fit line vary from year to year, perhaps with the solar cycle (Ogilvie 1972). The helium properties are also organized within the proton velocity streams in the solar wind (Asbridge et al. 1973; Hirshberg et al. 1974). In particular, in the Vela 3 data the helium abundance was about four percent throughout most of the stream structure, but fell to somewhat less than 2.5 percent just before the density peak at the leading edge of the stream. There was also a marked drop in the temperature ratio T_α/T_p from about four throughout most of the stream to values of less than three in a region centered on the density peak. In addition, the bulk velocity of the helium ions is some 20 km/sec larger than that of the protons after the density peak passes and remains about 10 km/sec faster for at least three or four days. The velocities are almost equal in the region of the stream before the density peak occurs.

3 - EVALUATION OF THE DATA

In this section we review the evidence available to us examining critically the results of each experiment which have so far been published (see figure 2). Before discussing these in turn, however, some general statements can be made.

Since h is a ratio, the values obtained by two given instruments depend upon the relative efficiencies of each for detection of helium and hydrogen ions. These quantities are determined by the secondary emission coefficients of surfaces and by detection thresholds rather than by the absolute density calibrations of a given detector, and determinations of h are probably much less liable to systematic intercalibration errors, than for example, values of either density alone. The helium ions in the solar wind are doubly charged and have four times the energy of the protons so that detection systems in general are more efficient for them than for protons, and a detector with a high efficiency for protons thus has an even higher efficiency for helium. If the efficiencies of two detectors are high, the measured values of h will agree even if the absolute density calibrations do not.

The absolute accuracy of determination of the bulk speed is the highest of any property of the solar wind, as it depends only on relative flux determinations, and essentially results from the measurement of a potential difference in the instrument. Since values of the average velocity $\langle v \rangle$ are used in our discussion, we point out that their absolute accuracy should be better than 5 percent, corresponding to $\sigma \approx 20$ km sec^{-1} for all the observations used here.

The helium abundances from the various plasma probes are presented in column 4 of table 1 and in the second panel of Figure 2. This figure is an extension of figure 5 of Bollea et al. (1972) in which they showed helium abundances reported for Vela 3, Explorer 34 and HEOS I. We have added data from Mariner II, Ogo 5, Explorer 43 and ALSEP, thus extending the data to cover more of the solar cycle. In order to evaluate the reality of the apparent systematic changes evident in figure 2, the accuracy of each of the determinations will be discussed in turn.

Mariner II

The Mariner II plasma probe collected data in 1962 and was the first instrument used to study helium in the solar wind. The instrument and data analysis are described in Neugebauer and Snyder (1966). In their data analysis Neugebauer and Snyder assumed the temperature of the alpha particles, T_α, to be four times that of the protons, T_p, and that the velocities of the two species were equal. Examination of over 10,000 spectra collected by Vela 3 shows that T_α/T_p varied only from 3.5 to 4.8 as u varied from 275 km/sec^{-1} to 625 km sec^{-1}. Thus the effects of the T_α/T_p assumption will not be expected to be dependent on the velocity interval in which the measurements are made and the assumption should be quite valid for all velocities.

The value of <h>, the mean value of h characterizing the entire period of observation, given in table I for Mariner II, differs from that derived by Neugebauer and Snyder (1966), although it is consistent with their values of <h> = 0.046 ± 0.038. M. Neugebauer has supplied us with the original three hour averages from which we constructed regression lines corresponding to various values of the goodness-of-fit parameter as defined in Neugebauer and Snyder (1968). The data from which the value $\langle h \rangle = 0.046$ was calculated was a highly restricted set, containing only eight percent of the total number of spectra collected by Mariner, and appears to have contained a helium enhancement event which significantly influenced $\langle h \rangle$. When the condition on the goodness-of-fit parameter is relaxed from ≤ 3 to ≤ 8, the data set is much less restrictive, containing some 23 percent of the observations, widely distributed with respect to bulk speed. The value of $\langle h \rangle$, and the slope, A, and h intercept, B are quite stable against variation with the value of the goodness-of-fit parameter. These are given in Table 1. Although we consider the value and error given here to be more representative of the whole Mariner results than that originally given by Neugebauer and Snyder, it should be clear that the uncertainty in these new values is large.

Vela 3

The helium abundance of the solar wind was studied by the Vela 3 plasma probe from July 1965 to July 1967. The Vela plasma probes and orbits are described in Bame *et al.* (1967) and Hundhausen *et al.* (1967). Helium observations are reported in Hundhausen *et al.* (1967) and a more extensive study of the two years of data is presented in Robbins *et al.* (1970). Robbins *et al.* state that a conservative estimate of the errors in computing the helium abundance in individual spectra is 25%. However, when averages of abundances are taken over many spectra the error of the average is less than the errors of the individual spectra, and a "best guess" error estimate for the average helium abundance is 10% (Bame, private communication).

In addition to error that may be introduced in the analysis of the spectra, a possible systematic error may have arisen in <h> since Robbins, et al. omitted from their study proton spectra that could not be accurately fitted with a single Maxwellian. Recently, Feldman et al. (1973) have examined proton spectra of this type and have interpreted them as streams of hydrogen moving relative to one another. They point out that the double streaming tends to occur in the rarefaction region of the velocity stream. The relative abundance of helium appears normal in this region (Hirshberg et al. 1974) so omission of these few spectra should not cause a significant error in the mean helium abundance reported by Robbins et al.

The Vela 3 data present an excellent opportunity to test the findings of Ogilvie (1972), that the relationships between the helium abundance and the solar wind velocity changes with solar activity. Although the Explorer 34 and 43 results were clearly different from the Vela 3 results, and from each other, it might be argued that the effect was purely instrumental. However, Vela 3 took data for two years, from July 1965 to July 1967, and the sun was very inactive from launch until March 1966. Subsequently there were a number of large proton flares. Thus, the data can be broken up into a quiet sun period (from July 1965 to March 1966) and a disturbed sun period (from March 1966 to June 1967). The mean helium abundance during the first period was .034, while the mean during the second period was .039. The average helium abundance has also been computed separately for each 25 km/sec velocity interval. Statistically significant results (i.e. the velocity interval contained more than 200 spectra) were available for velocity interval 300-325 up to 425-450. For a given velocity <h> was greater during the second period than during the first, with the single exception of the 300-325 km/sec interval, when the helium abundances were equal during the two periods. The differences were .005 or lower for velocity intervals up to 400 km/sec. At the two highest velocity points the differences in helium abundance became very marked. In the velocity interval 400-425 km/sec <h> was .034 during the quiet sun period and .045 during the disturbed period. At 425-450 km/sec <h> was only .036 for the quiet period compared to .048 during the disturbed period. Thus, the differences between the helium abundances for the quiet sun period and the disturbed sun were statistically significant, and increased with increasing solar wind velocity.

Explorer 34

The interplanetary helium abundance was studied by Explorer 34 from May 1967 to January 1968. The plasma probe and data analysis are described in Ogilvie <u>et al</u>. (1968). All the observations discussed in this paper with the exception of those taken by the instruments on Explorer 34 and Explorer 43, require numerical separations between helium and hydrogen during the data reduction process. The limitations on these procedures come from the possible presence of high energy "tails" to the velocity distribution function of the protons, for which a form must be assumed. The numerical separation is most inaccurate at times of low relative abundance and high plasma temperature. However, both h and T_p have been shown to be positively correlated with the plasma bulk speed by the Explorer 43 (Ogilvie 1972) and Explorer 34 (Burlaga and Ogilvie 1968) experiments which employ $\underline{E} \times \underline{B}$ separation. These positive correlations show that the proportion of time when h is low and T_p high is small. The effect of errors resulting from the data reduction procedures is expected to be small except at times of low bulk speed.

Since the limit of detectability was governed by an electronic background and was reached first for helium, the measurements of Explorer 34 are biased towards a condition of high solar wind flux. Ogilvie and Wilkerson (1969) discussed this effect at length, and showed that as the proton density limit above which the measurements were made was progressively raised the apparent value of n_α/n_p decreased. The number quoted in table I is for $n_p > 5$, and it is much more likely to be in error by being too high than too low. Vela 3 data (Robbins et al. 1970) showed a correlation coefficient between h and proton density of -0.12 so any systematic error is probably small. It should also be noted that Explorer 34 and Vela 3 made simultaneous measurements for several hours in July 1967, and during these periods the two probes were in agreement.

OGO-5

Data from this instrument while in the solar wind between 5 March 1968 and 30 April 1969 were kindly made available to us by M. Neugebauer. Averages of h for those rotations during which enough well distributed observations were made are shown in Figure 2. The instrument described by Neugebauer (1970) contained both a Faraday cup and an electrostatic analyzer, but all the presently discussed observations were made using the analyzer. Values of h were computed only if the helium flux in the peak channel was greater than 5×10^5 cm^{-2} sec^{-1}. Since spectra for which n_α was in the noise level were omitted from the data samples <h> is somewhat overestimated.

HEOS I

HEOS I observed the helium in the solar wind from December 1968 to April 1969 and from September 1969 to April 1970. For a description of the particle detector see Bonetti _et al_. (1969). Observations have been described by Formisano _et al_. (1970) and Bollea _et al_. (1972). This experiment covered over a year in the solar cycle, and the data indicates that the average abundance of helium was higher during the early part of the period than during the latter part of the period. Bollea _et al_. (1972) have suggested that this variation represents a solar cycle variation of <h>.

HEOS I was unable to detect a flux of less than 5×10^6 α particles cm^{-2} sec^{-1} (Formisano _et al_. 1970). Now, Vela 3 found that the density of α particles was less than 0.1 particles cm^{-3} for approximately one third of their spectra (Bame and Robbins, private communication). For α particle densities of less than 0.1 particles cm^{-3}, the plasma velocity must be greater than 500 km/sec in order to have α particle fluxes large enough to measure by HEOS I. Thus, the HEOS data at low velocities are biased toward high helium densities, and therefore towards high helium abundances.

This is illustrated clearly in Figure 7 of Bollea et al. (1972). Thus, <h> for HEOS I should be considered an upper limit.

Although not directly involved in the study of the solar cycle variation of the helium abundance, it is interesting to note the effect of the limit of detectable α flux on the apparent variation of h with proton flux. For a proton flux of 5×10^7 particles cm^{-2} sec^{-1}, the lowest value of h for which the α flux is detectable is ten percent. Thus, the increase of <h> to about 10% for low proton fluxes (5×10^7 particles cm^{-2} sec^{-1}) reported by Moreno and Palmiotto (1973) can be explained as an instrumental effect rather than a real decrease of <h> with proton flux. The HEOS flux data cannot be considered in conflict with the prediction that <h> will increase with proton flux made from theoretical considerations by Geiss et al. (1970).

Explorer 43

This plasma probe detected solar wind helium abundances between March 18 and April 10, 1971. Its principles of operation, the same as those of the plasma probe on Explorer 34, and the data have been discussed by Ogilvie (1972). In contrast to Explorer 34, in the case of Explorer 43 there was no sensitivity problem, helium densities below 0.05 cm^{-3} being readily measured, and helium being measurable during the whole data sample. The value of h was found to be only weakly dependent upon proton density. However, the experiment failed prematurely, and the data sample may not be fully representative of its epoch due to the variations from solar rotation to solar rotation, as discussed in section 4 and shown in figure 2.

ALSEP

The observations presented here are from the Apollo 15 Alsep. This instrument, consisting of an array of seven Faraday cups, is similar to the Apollo 12 Alsep instrument described by Neugebauer et al. (1972). Due to a local magnetic field, the values of proton density deduced from observations by Apollo 12 differ significantly from simultaneous OGO-5 observations and so are not used here. If there were such a magnetic effect for Apollo 15 Alsep, this would systematically alter h, since the deflection of a charged particle depends upon its magnetic rigidity. However, the field at the site of Apollo 15 was sufficiently small (C. P. Sonett, personal communication) that the effect was negligible. The present observations refer only to times when Alsep was on the sunlit side of the moon and in the solar wind. In the data analysis it is assumed $T_\alpha = 4\ T_p$ and $v_\alpha = v_p$. The values of h refer to times when $n_p \geq 3$, and with the instrument sensitivity of 2.5×10^6 charges cm^{-2} sec^{-1} for normal incidence, and assuming $U = 400$ km sec^{-1}, observations could be made for $h \geq 0.01$. Sensitivity considerations therefore do not introduce a bias into these data.

4 - DISCUSSION OF OBSERVATIONS

The results of all these experiments are given in Table I and as the second panel of Figure 2. In table I the 4th column gives the average abundance of helium for each experiment. In Figure 2 averages over several solar rotations are given as heavy horizontal bars. Each of the data points represents an average over a solar rotation. The outstanding characteristic of these solar rotation averages is that they are extremely variable from one rotation to the next. As pointed out earlier this can be due to a combination of two effects; first, that the solar wind often maintains a given value of h over periods of the order of days, and second the plasma probe samples the wind unevenly in each rotation. Thus, although probably exaggerated by sampling problems, the short period fluctuations represent an intrinsic variation of the quantity h.

A search was made for a heliographic latitude dependence of $\langle h \rangle$. This was motivated by the possible observation of such a dependence in the velocity and density of the solar wind (Hundhausen et al. 1971) and in the Vela 3 h data (Rosenberg et al.). Using the data set shown in figure 2 it was found that during those periods when the probes were at the greatest solar latitude ($\pm 7^{\circ}$ at the beginning of September and March), $\langle h \rangle = .042$, while when the probes were near the solar equatorial plane $\langle h \rangle = .045$. That is, there is no statistically significant evidence in these data for a heliographic dependence of $\langle h \rangle$.

A main purpose of this paper is to establish limits on the size of the solar cycle variation of the helium abundance. A cursory glance at Figure 2 suggests a variation in phase with the sunspot cycle from values of about 3.4 near minimum (Mariner II and Vela 3) to over 5 at maximum, i.e. a ratio of $\langle h \rangle_{max}$ to $\langle h \rangle_{min}$ of about 1.5. However, we believe that this is an overestimate of the effect. The values of $\langle h \rangle$ near maximum depend on Explorer 34, OGO 5 and HEOS 1. As pointed out in the discussion of the instruments, all of these experiments were biased so that the $\langle h \rangle$ they report is almost undoubtedly too high.

A lower limit on the size of the solar cycle variation of the helium abundance may be estimated as follows. It is not inconceivable that $\langle h \rangle$ reported by Explorer 34, OGO 5 and HEOS I are .01 too high, giving $\langle h \rangle$ as low as .04. Then if Vela 3 $\langle h \rangle$ were 10% too low the estimate for the first Vela year could be raised to about .037 and (recalling that Mariner II $\langle h \rangle$ is uncertain) the data is conceivably consistent with no solar cycle helium abundance variation whatsoever. However, we do not consider this to be the most likely explanation of the data. In the case of Vela 3, a trend in $\langle h \rangle$ occurs within the lifetime of a single instrument. This trend is continued by Explorer 34, which reported the same value of h for the solar rotation during which both Vela 3 and Explorer 34 instruments were observing. In addition, the general trend of all the data suggests a solar cycle variation in the helium abundance. Strictly speaking, if we include our estimated limits of error, the solar cycle change of the helium abundance can be given as $\Delta\langle h \rangle = .01 \pm .01$. That is to say, our best estimate of the variation is about .01.

The relationship between $\langle h \rangle$ and solar wind flux may also be studied using the data in Figure 2. In their theoretical paper on solar wind helium abundance Geiss et al. (1970) find that, in their model, there is a minimum proton flux necessary in order to raise helium into the solar wind and suggest, on the basis of this finding, that there ought to be a correlation between solar wind flux and helium abundance. It has already been pointed out (Robbins et al. 1970, Hirshberg et al. 1972, Ogilvie 1972) and Moreno and Palmietto 1973) that the data from individual plasma probe experiments do not show this effect. However, several objections can be made to these studies. Firstly, it may be that the instrument caused a bias in the data, as is clearly the case for HEOS I. Secondly, the three hour average solar wind flux measured at 1 A.U. is not representative of the flux at the sun because of the density peaks and rarefactions caused by the interactions of the solar wind velocity streams occuring in interplanetary space. The present study allows another test to be made of the proposed relation between proton flux and h, since we can compare the solar cycle trend in h with the trend in proton flux. In Figure 2 the smallest $\langle h \rangle$ was observed during the first 9 months of the Vela experiment (1965-1966), and the largest $\langle h \rangle$ was observed between late 1967 and early 1969. Montgomery et al. (1972) give twenty-seven day averages of the mass flux density from July 1965 to October 1969, from Vela 3 and Vela 4. The 27 day average proton flux tends to be higher in 1965 (small $\langle h \rangle$) than in 1967-69 (large $\langle h \rangle$). This is the converse of the effect expected by Geiss et al. This disagreement with the conjecture of Geiss et al. is however still not definitive. Although this study makes it clear that $\langle h \rangle$ does not increase with solar wind flux measured at 1 A.U., the conjectured dependence referred to $\langle h \rangle$ and the proton flux at the sun. In a given period of time, the flux at the sun could be relatively large and the flux at 1 A.U. relatively small if the large flux at the sun came from a sufficiently small solar area, and therefore the solar wind had to expand more markedly. Thus, the possibility remains that the conjecture of Geiss et al. could be correct, but only if the solar wind came on the average from smaller regions of the sun during the recent solar maximum than during minimum.

5 - DISCUSSION OF RESULTS

Our evaluation of the published data has shown that there is a solar cycle variation of $\langle h \rangle$ 0.01 ± 0.01, and a discussion of possible causes of the variation becomes appropriate.

The simplest explanation of the solar cycle variation would be that there was a relation between u and $\langle h \rangle$, shown by a linear regression, that this relationship would remain constant over the solar cycle, and that the variation of $\langle h \rangle$ would be caused by a solar cycle variation of u. This hypothesis can be readily rejected. Assume, for example, that the Vela 3 regression is the correct regression curve. Then, if we find $\langle h \rangle$ corresponding to $\langle u \rangle$ for each period, we find a variation of only a few tenths of a percent in $\langle h \rangle$. The situation is not significantly improved by using the velocity distribution measured by the various probes as collected by Gosling <u>et</u> <u>al</u>. (1971).

Another check on this hypothesis is to calculate regression lines separately for each instrument. These are shown in Figure 3, where it is seen, in agreement with Ogilvie (1972), that the regression lines change markedly from period to period and perhaps from instrument to instrument. A measure of the change in the regression line is to compare the value of $\langle h \rangle$ at some standard velocity for each of the regression lines. We have chosen 400 km/sec as the standard velocity, as shown by the dashed line in the figure. Column 5 in Table 1 gives $\langle h \rangle$ at 400 km/sec for each regression line. Columns 6 and 7 give the slope (A) and the zero velocity intercept (B) for each line. It is clear that no single regression line can represent the data collected during all periods during the solar cycle.

A second possible cause of the solar cycle variation is that there is a basic regression of $\langle h \rangle$ and u, and that in addition, there are superimposed helium enhancements due to transient events in the solar wind. Inherent in this explanation is the notion that there are two distinct types of processes by which material leaves the sun, and becomes part of the interplanetary medium (Parker 1963, Hirshberg et al. 1970). The first, and most common process is the expansion of the corona in a more-or-less steady state fashion that is normally described in treatments of the solar wind. The second is a transient process, as for example the sudden expansion that might be due to rapid coronal heating by a major flare (Parker 1963) or the remarkable coronal transients recently observed by the white light coronagraph on board ATM (MacQueen et al. 1974).

A systematic study of the relationship between solar wind helium enhancements and solar flares was carried out (Hirshberg et al. 1972) for the period of 1965-1967, using Vela 3 data. All plasma spectra that showed more than 15% helium were examined; 15% was chosen to cut down the sample size. There were 16 distinct periods of helium enhancements, 12 of which were clearly associated with interplanetary disturbances caused by major flares. The average velocity at 1 A.U. of the plasma containing the flare associated helium was 546 km/sec and ranged from 360 to 650 km/sec. Thus, flare associated enhancements will contribute more to raising the helium abundance at high velocities than at low velocities; thereby increasing the slope of the regression line. It is interesting to note that the slopes given in Table 1 are roughly proportional to the smoothed sunspot number, Figure 2. It should also be stressed that not all solar flare enhancements can be expected to show as much as 15% helium, since that number was chosen for convenience; there was no apparent break or change of slope in the h frequency distribution in the Vela 3 data (Robbins et al. 1970). A smaller enhancement maintained for a longer time, would be just as effective in raising $\langle h \rangle$. However, $8\% \leq h \leq 15\%$ was so common in Vela 3 data that the problem of flare association of these enhancements could not be studied in a statistically meaningful manner.

A rough estimate can be made of the frequency of helium enhancements required to explain the observed solar cycle variation of $\langle h \rangle$. Suppose the value of h remains constant = h_o except during an enhancement when it increases to H(t) for a period Δt hours. If we average h for a period of t hours near solar maximum, where $t \gg \Delta t$ and during which there are m enhancements,

$$\langle h \rangle_{max} = \frac{h_o \left(t - \sum_1^m \Delta t_r\right) + \sum_1^m \int_0^{\Delta t_r} H_r(t)\, dt}{t} \qquad (2)$$

If these enhancements are the only cause of variation, $\langle h \rangle_{min} \approx h_o$ and putting the ratio $\langle h \rangle_{max}/\langle h \rangle_{min} = 1.3$

$$0.3 = \frac{1}{t} \sum_{r=1}^{m} \left[\frac{1}{\langle h \rangle_{min}} \int_0^{\Delta t_r} H_r(t)\, dt - \Delta t_r \right]. \qquad (3)$$

If H(t) = 0.2, h = 0.033, Δt = 5 hr, somewhat extreme but not unrealistic nu derived from experiments, the number of events per hour, $\frac{m}{t} = \frac{0.3}{\Delta t \left(\frac{H}{h} - 1\right)}$, and approximately one event is required every 85 hours. That is, if the solar cycle variation of $\langle h \rangle$ were all due to major helium enhancement with the characteristics given above we would need an increase of about 100 events per year between solar minimum and solar maximum.

It is difficult to estimate the change in the number of helium enhancements that occurred during the solar cycle, since the single systematic study of that question covered only the two years of the Vela 3 period. That data analysis has been divided into two periods, a quiet sun period (July 1965 - February 1966) and a disturbed period (March 1966 - July 1967). During the first period only one enhancement to h $\geq$ 15% was seen, and no flare association could be established for that event although it was associated with an ssc and a small Forbush decrease. The other 15 enhancements took place during the second, high activity, period.

One may also try to make a rough estimate of the change in the number of enhancements by noting the change in the number of sudden commencements over the solar cycle. The notion here is that major flares cause interplanetary disturbances which propagate to the earth where they can be recognized by the ssc caused by the sudden increase in the dynamic pressure on the magnetopause which occurs when a shock arrives. Observationally, there is good evidence (Taylor 1968, Burlaga and Ogilvie 1969) that events reported as ssc's by more than 10 stations have a high probability of being caused by interplanetary shocks. However, not all helium enhancements are associated with sudden commencements (Hirshberg _et al_. 1972), not all sudden commencements are associated with major flares, and not all interplanetary shocks are associated with helium enhancements (Ogilvie and Burlaga 1974). Furthermore, recent numerical studies of the propagation of disturbances in a solar wind containing velocity streams (Hirshberg _et al_. 1974, Scudder and Burlaga 1974) have shown that the appearance of the disturbance is strongly influenced by the position in the velocity stream at which it is observed. For example, a disturbance may be shock-like in the low velocity region of a stream, and not shock-like in the high velocity region. Thus, for the same solar event an ssc might be produced if the earth were in one region of a stream and not in the other.

In spite of all this uncertainty it may still be instructive to estimate the number of ssc's. In the lowest panel of Figure 2 we show the number of ssc's derived from Bartel's musical diagram and compare it to the number of ssc's/year listed by more than 10 stations in the NOAA bulletin. (This latter number has been corrected by a few events by adding 1/10 the number of si listed by 10 stations. The correction ranged between 0 and 4.) We note that the number of ssc does not follow the mean sunspot number, and that the yearly number is about 30 or 40. We also estimated the number of transient flare events occurring at the sun by counting the number of flares of importance two or greater (D. Trotter, private communication). We note again that the number does not follow the smoothed sunspot number well, and that there are of the order of 30 or 40 events/year during active periods and perhaps 5 during solar minimum.

Thus, if we were to attempt to assign the .01 solar cycle increase in <h> to transient events only, and to use the observed number of sudden commencements or flares of importance greater than 2 as an estimate of the number of transient helium enhancements, we would apparently fall short by a factor of two.

Before leaving the question of the effects of transient phenomena on the helium abundance of the solar wind, attention must be drawn to the extremely interesting observations reported from the HAO white light coronagraph on Skylab (MacQueen et al. 1974). In their paper, MacQueen et al. describe only the coronal transient of June 10, 1973. They state that the coronal transient had the general appearance of a large magnetic loop, expanding outward from the sun; it expanded to a radius of greater than 2 $R_\odot$ and the material front in the case of this particular transient had a projected velocity of 450 km/sec when it was at about 4 $R_\odot$ (compare with the average transient velocity of solar flare helium enhancements, 630 km/sec (Hirshberg et al. 1972)). They further state that such coronal transients are not rare; more than two dozen having been observed during the first four months of Skylab. Since only preliminary studies of this type of coronal transients have been made at this early date, it is not yet known what their relationships are to other rapidly varying solar phenomena, such as solar flares, rising prominences etc. There is, of course, no information on the value of h characteristic of the plasma associated with these coronal transients, however, since the acceleration mechanisms operative in expelling this plasma from the solar corona is certainly different from the quasi-steady solar wind, it is reasonable to expect that h might not be the same within coronal transients and quasi-steady solar wind velocity streams.

We have found that, if there is a single basic regression of $\langle h \rangle$ and u, the solar cycle variation of u is insufficient to explain more than a few tenths of the observed $\Delta\langle h \rangle$, while, if we use flares or ssc as estimates of the transient events, they account for perhaps half of our best estimate solar cycle variation of $\langle h \rangle$. We must consider the possibility that the regression of $\langle h \rangle$ on u characteristic of the quasi-steady (non-transient) solar wind varies with the solar cycle. Theoretical discussions of the expected values of $\langle h \rangle$ (Geiss et al. 1970, Yeh 1970, Nakada 1970, Alloucherie 1970, see also Hirshberg 1973, for a brief review) indicate that the expected $\langle h \rangle$ is very model dependent, and in particular is very dependent on the velocity profile of the solar wind low in the corona. The problem has been treated only for the simplest solar wind models. At the present time there is such a proliferation of solar wind theories (c.f. Hundhausen 1972) that very little can be said. However, we note that in order to contribute to the solar cycle variation of $\langle h \rangle$ the solar wind must vary in such a way that, for a given velocity, h increases during the solar cycle, while the proton density may decrease.

6 - SUMMARY AND CONCLUSIONS

A careful analysis of the solar cycle variation of the observed h indicates that there was a solar cycle variation of $\langle h \rangle$ of $.01 \pm .01$; $\langle h \rangle$ being larger at solar maximum than at minimum. If the flux of the solar wind varies so that flux is lowest at maximum (as has been suggested by Diodato et al. (1974)) then the conjecture that $\langle h \rangle$ varies as the proton flux at the sun can be correct only if the solar wind comes from a smaller area of the sun at maximum than at minimum. The solar cycle variation of $\langle h \rangle$ is not due to solar cycle differences in u, but instead, the regression of $\langle h \rangle$ and u varies with the solar cycle. A rough estimate of the frequency of transient solar wind events indicates that solar cycle variation of their frequency can account for perhaps half of the best estimate of the variation of <h>. In this regard, a study of the type of coronal transient recently discovered by Skylab may prove very important. Other possible contributors to a solar cycle variation of <h> include systematic changes in <h> for the same u at different parts of the solar cycle. Exploration of this possibility may lead to new theoretical understandings of the solar wind near the sun.

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TABLE 1

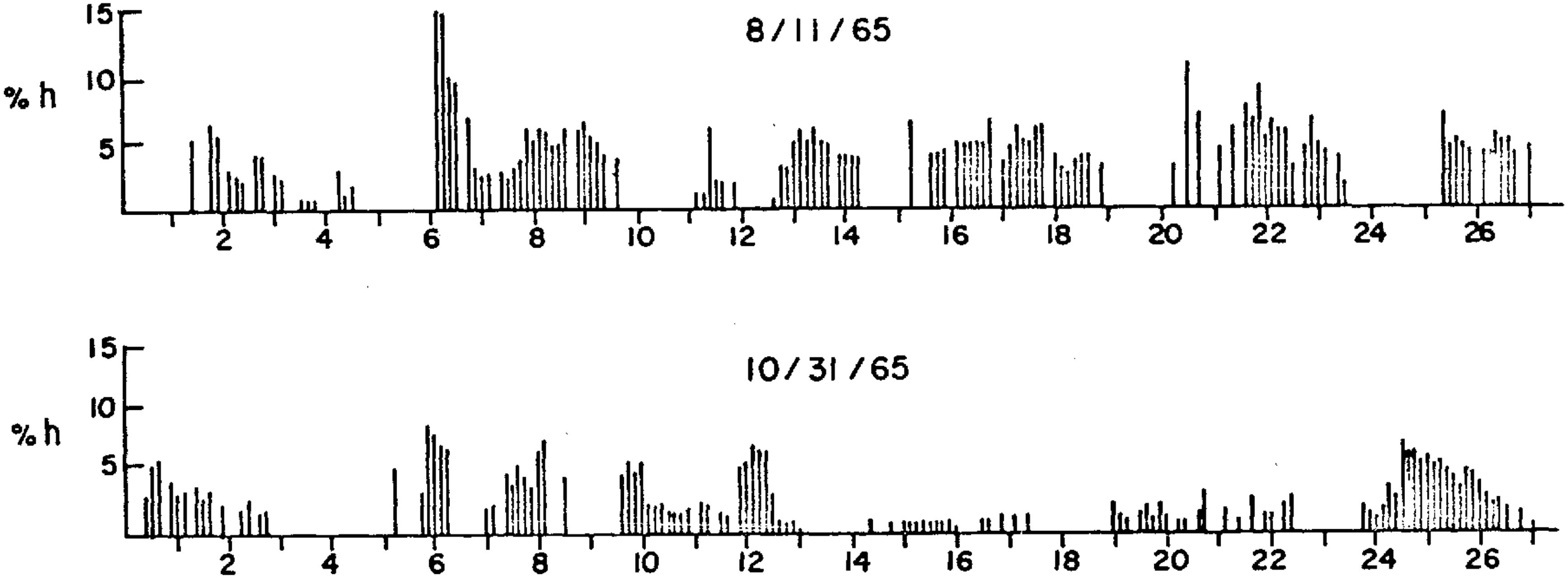
Year	Experiment	$\langle u \rangle$ km sec	$\langle h \rangle$ %	$\langle h \rangle$ u = 400	A	B	Remarks
1962	Mariner II	480	3.2 ± 1.0	3.0	0.35	1.6	newly adjusted values, 3 hr. average
1963							no observations
1964							no observations
1965	Vela 3	410	3.4 ± 0.4	3.4	0.8	0.2	period of low solar activity
1966	Vela 3	440	3.9 ± 0.4	3.5	1.2	-0.7	period of high solar activity
1967	Exp. 34	439	$5.1 {+0.0 \atop -1.0}$	--	--	--	30 min. averages, high density
1968-69	Ogo 5	480	4.6 ± 1.0	4.25	2.1	-4.5	
1969-70	Heos 1	445	less than 5.1	4.4	2.2	-3.2	n_α flux $> 5 \times 10^6$ α cm^{-2} sec^{-1}
1971	Exp. 43	408	4.7 ± 0.7	4.5	1.4	1.4	only one solar rotation
1971-72	ALSEP	402	4.1	4.1	0.57	1.7	

Figure Captions

Figure 1. The three hour average values of h, from Vela 3. The date of the first day of the solar rotation is given above each line. Note the long periods during which h was far from the two year average of 3.7%.

Figure 2. The solar cycle variation of the smoothed sunspot number is given by the points in the top panel. The circles represent the slopes of the least squares fit lines between $\langle h \rangle$ and solar wind velocity (see figure 3). The observed solar wind helium abundance h is given in the second panel. An evaluation of the accuracies of these data leads to the conclusion that the solar cycle variation of $\langle h \rangle = 0.01 \pm 0.01$. The bottom panel shows the solar cycle variation of major flares (solid line) and of ssc as defined by Bartels' diagrams (O) and as listed (X) in Solar Geophysical Data, NOAA. The solar cycle variation of the frequency of these transient events is not sufficient to account for the variation of $\langle h \rangle$.

Figure 3. The relation between velocity and helium abundance as determined from indicated plasma probes. HI = HEOS I, E43 - Explorer 43, OV2-OGO5 from Nov. 1968 to April 1969 (the earlier data were to sparse to yield a meaningful line), V3I = Vela 3 from July 1965 to March 1966, V3II = Vela 3 from March 1966 to July 1967, MII = Mariner 2.


8/11/65
10/31/65
% h
15
10
5
2
4
6
8
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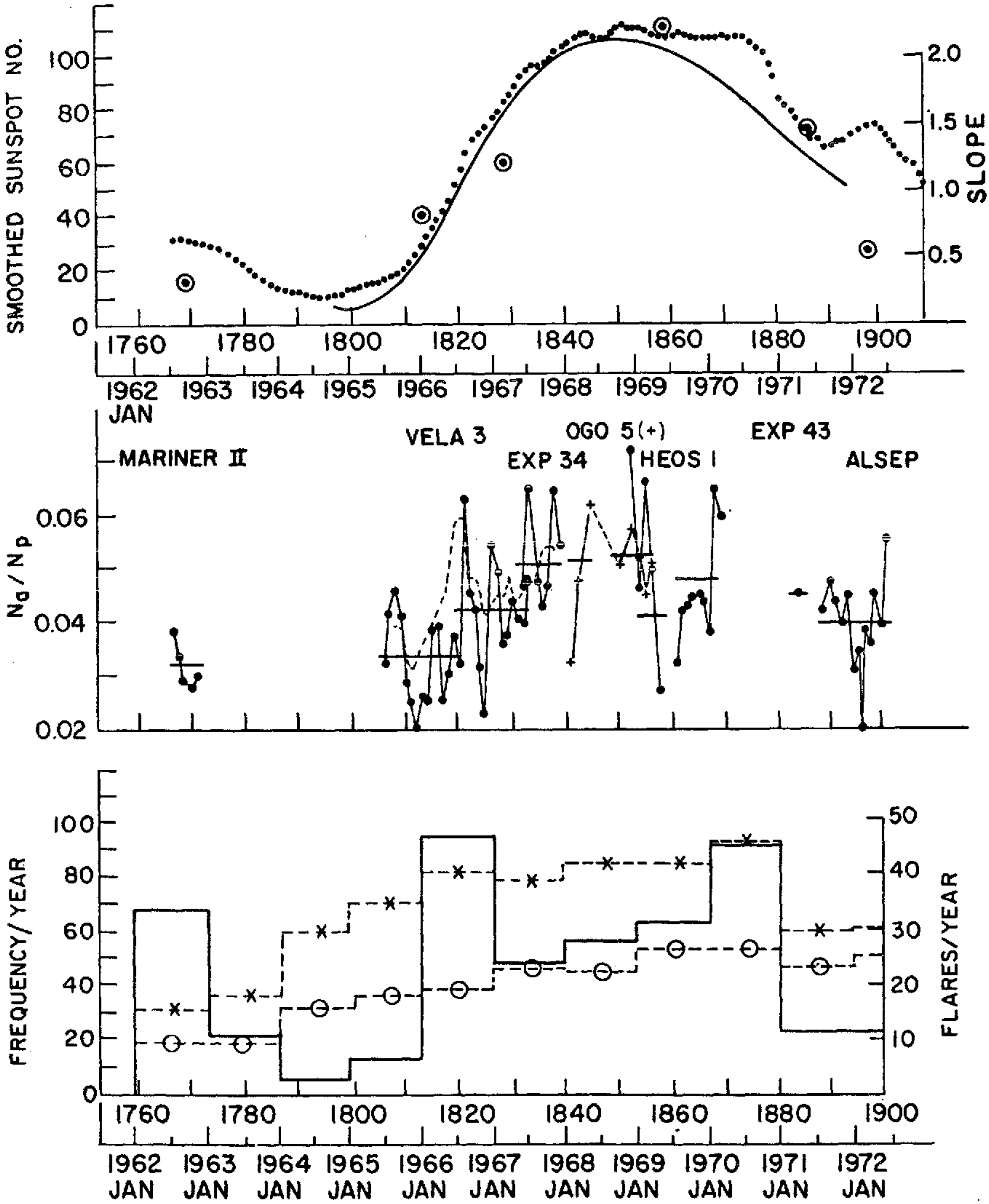
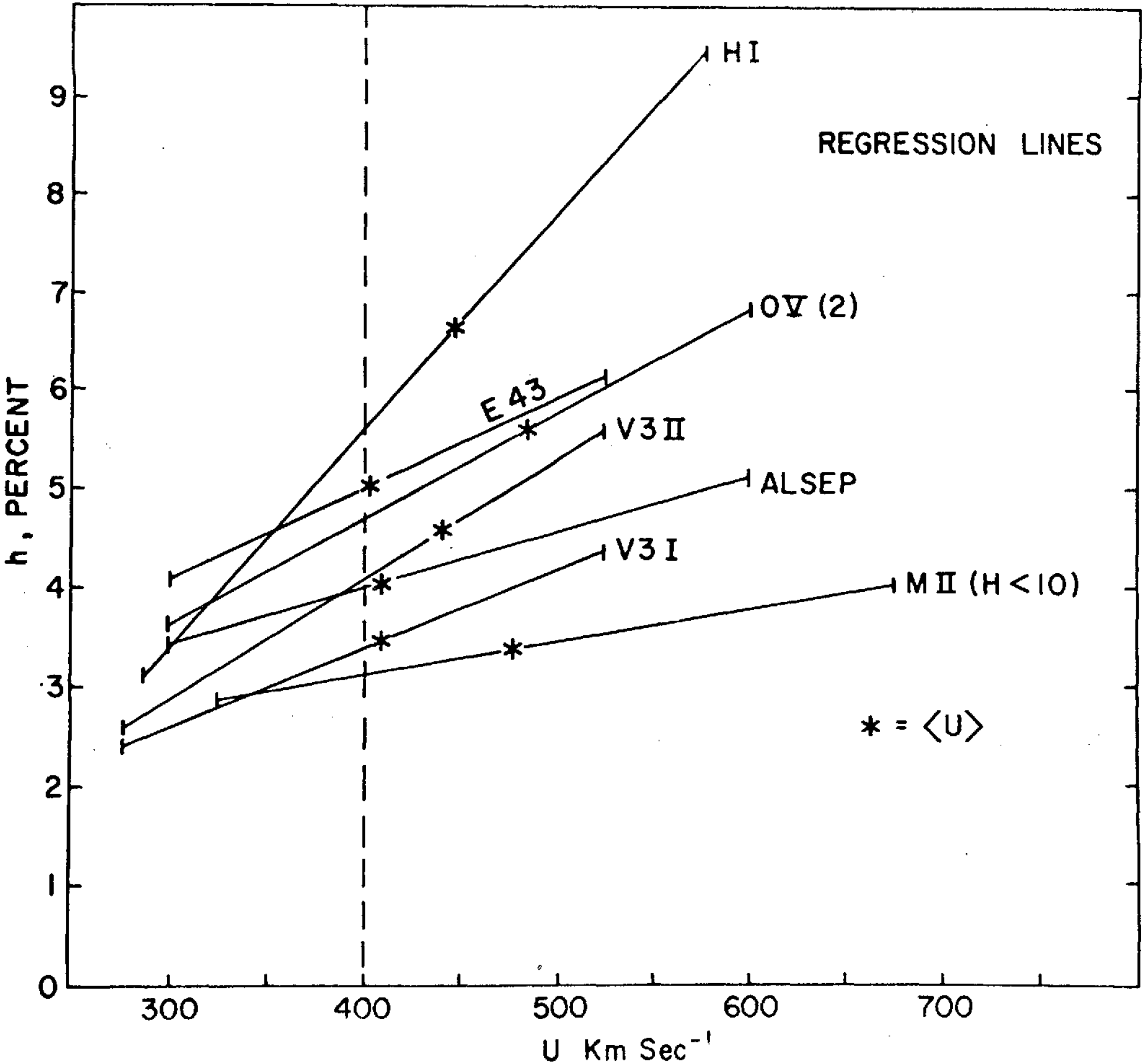
12
14
16
18
20
22
24
26



SMOOTHED SUNSPOT NO.
0
20
40
60
80
100
SLOPE
0.5
1.0
1.5
2.0
1760
1780
1800
1820
1840
1860
1880
1900
1962 JAN
1963
1964
1965
1966
1967
1968
1969
1970
1971
1972
MARINER II
VELA 3
OGO 5(+)
EXP 34
HEOS I
EXP 43
ALSEP
N_α / N_p
0.02
0.04
0.06
FREQUENCY/YEAR
FLARES/YEAR
10
20
30
40
50
1962 JAN
1963 JAN
1964 JAN
1965 JAN
1966 JAN
1967 JAN
1968 JAN
1969 JAN
1970 JAN
1971 JAN
1972 JAN



REGRESSION LINES
H I
O V (2)
E 43
V3 II
ALSEP
V3 I
M II (H<10)
* = ⟨U⟩
h, PERCENT
U Km Sec^{-1}
0
1
2
3
4
5
6
7
8
9
300
400
500
600
700

NASA-GSFC

35