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Solar Wind Observations with the Ion Composition Instrument aboard the ISEE-3 ICE Spacecraft

K. W. Ogilvie
NASA/Goddard Space Flight Center
Laboratory for Extraterrestrial Physics
Code 692
Greenbelt, MD 20771

M. A. Coplan
Institute for Physical Science and Technology
University of Maryland
College Park, MD 20742

P. Bochsler and J. Geiss
Physikalisches Institut
University of Bern
Bern, Switzerland

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This paper discusses the principal observations obtained by the Ion Composition Instrument (ICI) flown on the ISEE-3/ICE spacecraft, which was in the solar wind from September 1978 to the end of 1982, before being directed to the far magnetotail of the Earth. Almost continuous observations were made of the abundances of $^{3}He^{++}$, $^{4}He^{++}$, O^{6+}, O^{7+}, Ne, Si and Fe in various charge states, and of their bulk speeds and temperatures.

The results show that there is a strong tendency in the collisionless solar wind for the ionic temperatures to be proportional to the masses. For heavier ions these temperatures exceed typical coronal electron temperatures. $^{4}He^{++}$, especially in high speed streams, moves faster than H^{+}, and travels at the same speed as heavier ions. The mechanism leading to this heating and rapid streaming is still not entirely clear.

Because the ICI made continuous observations over long periods of time, the abundances of the minor ions obtained are representative of the solar wind. They agree well with corresponding abundances obtained from observations of Solar Energetic Particles (SEP's); suggesting that both solar wind and SEP's are drawn from the corona. Striking features of both solar wind and SEP ion populations are the overabundance of Si and Fe with respect to solar system abundances, and the under abundance of He. The latter discrepancy appears to result from gravitational fractionation in the lower corona and the high first ionization potential of He, as long suggested. The reason for the former discrepancy is not completely understood, but appears to be related to the low first ionization potentials of Si and Fe.

We have analyzed hourly averages of the abundance of $^{4}He^{++}$ in six month blocks, during the 4 1/3 year period which covered the maximum of solar cycle 21. The variation with solar activity is consistent in amplitude with results obtained during solar cycle 20, and shows more

structure. The probable causes of the variation of helium abundance with solar activity is the increased frequency of helium-rich events near solar maximum.

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Introduction

The existence of the solar wind was inferred by Biermann, (1951), from studies of comet tails. The experiment of Neugebauer and Snyder, (1966) aboard the spacecraft Mariner 2 was the first to show that, despite large variations in speed and intensity, the solar wind was omnipresent in the interplanetary medium. The measurements made with their instrument on Mariner 2, which selected ions by their energy per charge, E/Q, revealed the presence of a low concentration of an ion with twice the energy per charge of the protons, which comprise the bulk of the solar wind. It was concluded that the ion was doubly charged helium, $^4He^{++}$, and this was subsequently confirmed directly by Ogilvie et al., (1968) with an instrument combining both velocity and energy per charge measurements, to give the mass per charge (M/Q) of the solar wind ions. The only other possible ion with M/Q = 2, (H_2^+) is almost non existent at the high temperature of the solar corona.

Bame et al., (1968), using an improved E/Q analyzer, reported the presence of other elements (O, C, N, Si, Fe), and they and others (Holzer and Axford, (1970)); Lange and Scherb, (1970); Asbridge et al., 1970)) discussed and compared the data with respect to solar, solar system, and galactic abundances. General agreement was demonstrated, but some differences were noted. For example, Hirshberg, (1974) discussed 5 observations of solar wind Fe ions, indicating an abundance 2-3 times greater than that in the photosphere. Besides Fe, abundances were measured for the elements S and Si by Bame, (1975), $^3He^{++}$ and $^4He^+$ were also detected.

Subsequent work by the Los Alamos group included the analysis of a long series of He observations by Robbins et al., (1970), and extensive studies of post shock flows, (Borrini et al., (1982a)), and of high ionization states (Fenimore, (1980)). The variation of helium abundance with time in the region of sector boundary crossings has been studied by Borrini et al., (1981), and helium enhancements and their relation to coronal mass ejections by Borrini et al, (1982b).

An entirely different approach for studying the solar wind composition was used in the Apollo program: Solar wind atoms were collected in foils at the lunar surface for investigation in the laboratory. Very precise data on the elemental and isotopic abundances of He, Ne, and Ar for five different periods between 1969 and 1972 were obtained (cf. Geiss et al., 1972).

A disadvantage of E/Q measurements in the solar wind with electrostatic analyzers is that separation of ionic species depends upon the thermal velocity of the measured ions. By contrast a laboratory mass spectrometer has an ion source supplying singly charged ions of very low effective thermal speed; in the solar wind, however, each element is usually represented by several charge states, a consequence of the high electron temperature in the corona, and these ions have high and variable thermal speeds, often only about an order of magnitude less than the bulk speed of the plasma. The identification of minor ions in the solar wind by the Los Alamos group was most successful at low flow speeds, in conditions of high density and low temperature. Measurements of ion composition over the full range of solar wind thermal and flow velocity require instruments that go beyond the single parameter measurements of electrostatic energy analyzers.

The Ion Composition Instrument (ICI) on the ISEE-3/ICE spacecraft couples a high resolution electrostatic analyzer with a stigmatic Wien velocity filter (Coplan et al., (1978)). Ions entering the instrument pass through the filter before the analyzer. The narrow pass band of the filter can be centered at velocities within the range 300 to 620 kms^{-1}. By combining the knowledge of ion velocity and energy per charge, the mass/charge of the detected ions is determined, within the resolution of the instrument under all solar wind conditions. The ICI has operated successfully from launch in August, 1978 to the present. In addition to solar wind measurements, it has made the first observations of the composition of the distant magnetotail of the earth (Ogilvie and Coplan, (1984)) and of the composition of the comet Giacobini-Zinner (Ogilvie et al., (1986); Coplan et al., (1987); Geiss et al., (1986)). The solar wind data set presented here covers the period from August, 1978 to December, 1982 when the spacecraft was at the forward libration point, L_1, 1.5 x 10^6 km upstream from the earth.

The high velocity limit of the ICI is 620 km/s. Though higher velocities do occur, this limit is sufficient to permit observations for over 90% of the time, including many examples of high speed streams and shocks. At the highest velocities the energies of heavy ions such as Fe are sufficient to be detected by solid state devices such as those of Mitchell et al. (1981), and Ipavich et al. (1986), providing an independent check of the ICI results by an entirely different technique. Another more extensive check can be established by comparing with the ^{3}He, ^{4}He and Ne lunar foil measurements obtained during the Apollo flights, Geiss et al., (1972). The agreement among the results of the three techniques gives us confidence in the accuracy of our knowledge of these abundances and their variability.

Abundances from the present data set, measured over sufficiently long times to be representative, are unbiassed average values, and can be compared in a meaningful way with solar system abundances and used as a benchmark for theoretical models for solar wind acceleration and fractionation. In addition, the dynamical properties of individual ions can be obtained from the ICI data. In particular, differences in bulk velocity and thermal velocities among different ion species have been measured.

Ion velocities and velocity differences in the solar wind

A sustained difference ΔV between the bulk velocities of two ion species in the solar wind is only possible along the magnetic field direction (Neugebauer, 1976). For example, for $^4He^{++}$ and H^+,

$$\bar{V}_{^4He^{++}} - \bar{V}_{H^+} = \pm \Delta V \, \hat{b},$$

where $\bar{V}_{^4He^{++}}$ and $\bar{V}_{H^+}$ are the bulk velocities of the ions and $\hat{b}$ is a unit vector along the magnetic field direction. The helium-hydrogen velocity difference was the first to be measured (see references in Ogilvie et al., (1982)), and was observed in high speed flows, where its magnitude appeared to be limited to the local Alfvén speed. Observations from the Helios spacecraft (Marsch et al., (1982)) show that the velocity difference for a given V_{H^+} increases with decreasing heliocentric distance, as does the Alfven speed. Velocity differences tend to be destroyed by Coulomb collisions (Neugebauer and Feldman, (1979); Klein et al., (1985)), but in low density regions they can be observed out to at least 4 AU (Goodrich et al., (1979)). It is thus reasonable to suppose that velocity differences are set up in the corona even though there may be mechanisms in the interplanetary medium which sustain them. To drive high-speed streams, energy must be supplied by some process well beyond the critical point of the solar wind expansion. It has long been suggested (see Isenberg and Hollweg, (1983)) that the interspecies velocity differences are set up by the same process. At low flow speeds when densities are often high, collisions between protons and other ions are frequent, and velocity differences are suppressed. The velocity differences are presumably related to the acceleration and heating of solar wind ionic species. No fully successfuly theoretical treatment of this process has been carried out, and a comprehensive survey of velocity differences for higher masses and charges remains worthwhile.

The ICI does not have sufficient dynamic range in flux to measure both rare ions and protons. The velocities of the oxygen and iron ions have been compared with that of the helium, and simultaneous comparisons between the ICI helium velocities and proton velocities measured by the solar wind plasma instrument on ISEE-3, (provided by experimenters from Los Alamos National Laboratory (Bame et al., (1978)), have been carried out separately and are described by Ogilvie et al., (1982).

Figure 1a shows the ratio, $\Delta V/V_A$ for times when the helium velocity was between 300 and 400 km s^{-1}, (here ΔV is the difference between the measured helium and hydrogen speeds uncorrected for magnetic field direction and V_A is the Alfven speed). Figure 1b is similar, but for times when the helium velocity was between 400 and 500 kms^{-1}. There is a marked tendency for the helium velocity to exceed that of the protons by a substantial fraction of the current Alfven speed, especially at higher bulk speed, whereas there is no evidence within an uncertainty of a few percent for any difference in velocity between the $^4He^{++}$ and $^{16}O^{6+}$ ions, as shown in Figure 2.

Figure 3, from Schmid et al., (1987) shows a histogram of (V_{Fe}-V_{He}) based on 6636 individual measurements. The average velocity of these Fe ions was 426 km s^{-1}. The average velocity difference is 3 km s^{-1}, and the standard deviation was 15 km s^{-1}. The sample included higher than usual densities and lower than usual kinetic temperatures, because of criteria tending to select small velocity differences. Nevertheless, Schmid et al., (1987) found the following linear relation to represent the strong correlation between V_{Fe} and V_{He},

$$V_{He}-V_{Fe}=(2.5\pm0.9)+(0.049\pm0.003)\ (V_{He}-410.5)$$

where the velocities are in km s^{-1}.

This predicts a slip of ~ 15 km s^{-1} at 600 km s^{-1} of iron ions with respect to $^4He^{++}$ ions, which is small compared to a typical Alfven speed. Schmid et al., (1987) tentatively interpreted their observation as a consequence of the decrease of Alfven speed with increasing heliocentric distance and suggested that iron ions are more strongly coupled to the Alfven waves than are helium ions. Alternatively, residual Coulomb collisions, which preferentially affect ions in high charge states, may be responsible.

On the basis of these extensive velocity measurements we conclude that the minor ions generally move with the helium, faster than the protons. There is a tendency for the heaviest ions to lag slightly behind the $^4He^{++}$ at high speeds. A hint of this tendency was indicated in measurements by Mitchell et al., (1981). The theory, as presented by Isenberg and Hollweg, (1983) and Marsch et al., (1982) predicts acceleration of minor ions with respect to protons, but the measured ambient wave power is too low for it to produce velocity differences in agreement with observation. Isenberg and Hollweg, (1983), propose to tap the higher power at lower frequency by invoking the operation of the turbulent cascade, for example, Tu, (1988).

A process which we observed that altered the differential velocity between protons and helium is deceleration by the electrostatic field of interplanetary shocks. During a study of oxygen ion velocities in the solar wind (Ogilvie et al., (1982)), it was observed that passage of forward interplanetary shocks past the spacecraft decelerated the ions in the frame of the shock, and, in particular on July 6, 1979 changed the sign of the velocity difference between helium ions and protons from positive to negative, Fig. 4. This occurred because the electrostatic potential difference across the shock slows ions with different charge to mass ratios by different amounts as they cross it. Similar observations have been made by Zastenker and Borodkova, (1984), and Zastenker et al. (1986). This is the only mechanism which has yet been observed producing differential motion between ionic species.

Y. C. Whang, (1986) has postulated the existence of standing slow shocks in the flow above coronal holes, the sources of high speed streams, at a heliocentric distance at about 6-10 R_S. Preliminary consideration shows that the effect of such a structure would be to introduce a positive velocity difference between the helium and hydrogen ions. Schwartz et al., (1987) show that about 10% of the incident energy is thermalized. The shock, would, however, be rather weak, with a density ratio of order 2. On passing through such a shock, minor ions would be accelerated electrostatically with respect to the protons, but would not initially travel with the same speed as the helium. Thus the model requires a mechanism to produce the observed equality of speed between helium and other minor ions which is generally observed. We mention this effect here because (a) observations might be possible using minor ions to verify the existence of the slow shock, and (b) a "seed" velocity difference might be set up by such a shock, which would be automatically present in high speed streams and might be later amplified by the wave field.

Kinetic temperatures of solar wind ions

An important and interesting fact about the solar wind is that the thermal speeds w_i of all the constituent ions tends to be equal;

$$\frac{3}{2}\,kT_i = \frac{1}{2}\,m_i w_i^2.$$

As a consequence, the temperatures of the ions T_i, are proportional to their masses, m_i,

$$\text{or } T_i = \text{Const.}m_i. \qquad (1)$$

This was pointed out with reference to helium by Neugebauer, (1981) and others, and has been discussed for He, O and Fe ions by Schmidt et al., (1980) who used data from ISEE-1, Ogilvie et al., (1980) and Bochsler et al., (1985).

The "kinetic temperatures" measured by the ICI are a mixture of the parallel and perpendicular temperatures defined with reference to the direction of the magnetic field. This complicates the relation between the measured temperatures and the ion velocity distribution function. Furthermore, the observed temperature changes with the magnetic field direction, assuming a temperature anisotropy to be present. On the other hand, the ratios between temperatures of different ions determined from the same spectrum are independent of the magnetic field direction, neglecting time aliassing, and so the validity of eq. (1) can be tested for different ions using data from ICI. These temperatures are derived by fitting convected Maxwellian velocity distributions to the data, which form a cut through the 3-dimensional distribution function. When a reasonable fit cannot be obtained the data are discarded, but only a few percent are lost in this way. Thus the results refer to the major part of the observing time; it is known that several kinds of pathological forms of velocity distribution, such as "double humped" structures, (usually related to the interaction of high speed streams with plasma moving more slowly) occur at times, and the results discussed here do not apply to these times. A correction, normally rather small, has been applied for the intrinsic velocity resolution of the instrument, which is equivalent to about 10^4 K for helium.

If sufficient wave power were to be present in the frequency range corresponding to the measurement time of the instrument, non-thermal velocity fluctuations, due for example to Alfven waves, could be taken for thermal fluctuations. This might, in principle, be true of bulk speed fluctuations. However, estimates (Ogilvie et al., (1980)) show these effects to be quite negligible.

We have derived temperatures and thermal speeds for $^4He^{++}$ and oxygen. Even though the flux of Fe ions is near the threshold of sensitivity of the instrument, it has been possible to derive Fe temperature estimates also. The charge states (10 to 13) characterizing Fe in the solar wind put it an M/Q range where it is free from interfering ions. Also, Fe is overabundant in the solar wind with respect to its solar system abundance. These two facts make Fe temperature estimates possible. The result of the initial survey by Ogilvie et al., (1980), the work of Bochsler, (1984) and Bochsler et al., (1985) confirm the presence of a strong tendency in the non-collisional solar wind for the minor ions, from He up to Fe to be characterized by temperatures approximately proportional to their masses (equal thermal speeds).

In Figure 5 we see a plot of $^4He^{++}$ bulk speed and temperature, and the temperatures derived for O^{6+}, O^{7+} and Fe, for the period May to July 1979, from Bochsler et al., (1985). There are extremely good correlations among the four temperatures, with high kinetic temperatures occuring at the higher speeds as is the case for protons (Burlaga and Ogilvie, (1970)). At the lowest speeds (highest densities, corresponding most closely to collisional conditions), the temperatures of all the ions fall precipitously. The highest temperatures obtained for oxygen, and the usual temperatures for iron, are significantly above the electron temperature in the corona, ~ 2 x

10^6 K. The observed correlation between the temperatures of Fe ions and helium is not so high as that between oxygen and helium, but this probably reflects the large uncertainties in the determination of the Fe temperatures. Even so, Figure 5 provides clear evidence that the fast solar wind is heated after it leaves the corona by a mechanism which tends to impart equal thermal speeds to the minor ions, at least up to M/Q = 5-6.

Abundances and their variations

We now discuss the observations of ion abundances in the solar wind made between August, 1978 and December, 1982. The ions measured include ^3He, ^4He, O, Ne, Si, and Fe. For each of the species the measurements cover almost the full range of solar wind parameters rather than being based upon the analysis of a few samples taken under particular conditions. The results are exhibited as contour plots of the log of the flux of the minor ion versus the log of the $^4He^{++}$ flux; the contours connect regions of constant number of observations. The size of the regions is indicated on the diagrams. The fluxes are expressed in units of particles m^{-2} s^{-1}. In these plots a constant abundance is represented by an almost straight line as the solar wind flux changes. The helium results are compared with the proton flux and also exhibited separately as a function of time, as discussed below.

The shapes of the contour plots reflect the convolution of measurement uncertainties and natural variability. The averaging periods have been chosen to reduce statistical uncertainty by making the standard deviation for the various measurements similar to one another. For example. Fig. 6 is the contour plot of log ($^3He^{++}$ flux) vs. log ($^4He^{++}$ flux), constructed from 14000 hourly average observations. The dots indicate the results of individual $^3He^{++}$ and $^4He^{++}$ determinations by the foil method during the Apollo flights, identified with the corresponding Apollo flight number (Geiss et al., (1972)). Coplan et al., (1984), concluded that the best value of the average [$^4He^{++}$]/[$^3He^{++}$] was 2050 ± 200; the weighted average of the Apollo foil measurements is 2350 ± 120. The agreement between the

$^3He/^4He$ ratios obtained by the two entirely different techniques is remarkable. A small variation with solar activity was observed, and the ratio is more nearly constant at high than at low solar wind speeds. The pear shaped contours probably reflect the fact that the uncertainities in the measurements are greatest at low fluxes. Examination of the measurements as a time series indicates that there are periods of substantial intrinsic variability. To obtain an abundance of ^3He referred to H, we require a value of $[^4He^{++}]/[H^+]$. Normally this ratio is highly variable, but Bame et. al., (1977) have observed that it is more nearly constant in high speed streams than in the low speed solar wind, and ICI results support this observation. Bame et al. (1977), have shown that the helium abundance in high speed solar wind flows at 1 AU has a value of 0.048 ± 0.005. Such flows, from regions on the sun where ther magnetic field lines are open, may provide the best helium abundance measurements. Taking our average value for the ratio in high speed streams, (1900 ± 200), and the Bame et al., (1977) value for $[^4He^{++}]/[H^+]$ in high speed streams, 0.048, we obtain a relative abundance of $^3He^{++}$ of $2.6 \pm .2 \times 10^{-5}$.

The abundances of the minor ions other than helium are obtained by a minimization calculation. The charge state distribution of an element depends nonlinearly on the "freezing-in" temperature (Hundhausen, (1972)). By determining the best fit (in the least squares sense) between predicted and observed counts at given M/Q settings both abundances and an estimate of "freezing-in" temperature was obtained. This procedure takes into account the variation of instrument parameters with ionic mass, charge, and velocity (Bochsler et al., (1986)).

Figure 7 shows contours of log (O flux)vs log (He flux), Bochsler et al., (1986), with superposed lines corresponding to [He]/[O]= 60, 80, 100. The best average value is 75 ± 20, and a weak positive correlation with solar activity was detected, represented by

$$\log([He/[O]) = 1.6 \times 10^{-3} R_z + 1.696,$$

where R_z is the Zurich sunspot number.

This relation predicts a variation of the [He]/[O] ratio from about 50 to about 90 in a typical solar activity cycle. The [He/[H] abundance also increases with solar activity by about a factor of two, so that the oxygen abundance (with respect to hydrogen) remains nearly constant, independent of activity, as one might expect for a value characteristic of the solar corona.

Observations of neon (Bochsler et al., (1986)) (rather well isolated in a M/Q spectrum), obtained from a sample of several thousand spectra at the highest resolution, are shown in Figure 8. Again, the dots refer to Apollo foil observations. The average value for [He]/[Ne] is 536 ± 250; with most of the uncertainty being attributable to counting statistics. The Apollo foil measurements for the [$^{4}He/^{20}Ne$] ratio is 570 ± 70 (Geiss et al. (1972)); again the agreement is excellent.

In order to reduce statistical uncertainties (Bochsler, (1987)) used daily average determinations of the abundance of Si during the period August, 1978 to August, 1979, Figure 9. Here the uncertainty in the average value [He]/[Si] = 300 ± 150 also probably arises largely from statistical fluctuations.

Finally, Figure 10 shows the result of daily average determinations of log (Fe flux), vs. log (He^{++} flux) possible because Fe, although present in several charge states (Fe^{+10} to Fe^{+13}) in the solar wind, is both over abundant (see below) and isolated in M/Q spectra (Schmid et al., (1988)).

Table I compares these results with two recent compilations of abundances derived from observations of Solar Energetic Particles, (SEP) by Cook et al., (1984) and McGuire et al., (1986). Agreement among the measurements made under a wide variety of solar wind conditions, is well within the experimental uncertainities; we conclude that both SEPs and the solar wind seem to be drawn from the same population, which we know for the solar wind is the corona. In Table II we have converted the ICI abundances for ^{3}He, O, Ne, Si and Fe to abundances with respect to H, using $[^4He]/[H] = 0.040$. Comparing the abundances with solar system abundances, we see that there are two major discrepancies. Helium is definitely underabundant, as concluded by many authors (Neugebauer, (1981)). This is generally believed to be partly due to the reduced drag force exerted by the protons on the helium ions (Geiss et al., (1970)), to extract them from the gravitational potential well in the lower corona, and partly due to a separation process between ions and atoms, to be discussed below. Although we find oxygen and neon solar wind abundances in good agreement with those quoted for the solar system, both silicon and iron are over abundant in the solar wind by a factor of about four. It has been suggested that the SEP abundance data can be organized according to first ionization potentials, (Hovestadt, (1974)), ions having low first ionization potentials being overabundant (Si, 8.15 eV; Fe, 7.87 eV). A similar mechanism in which ionization early in the process of solar wind acceleration would favor incorporation of a species into the flow could explain the observations, (Meyer, (1985); Geiss and Bochsler, (1985)).

Helium abundances in Solar Cycle 21

The ICI instrument on ISEE/ICE has allowed us to acquire an almost continuous set of observations of the density of $^4He^{++}$ over the time period August, 1978 to the end of 1982. In the previous discussions, abundances of heavy ions have been referred to helium, the most abundant ions regularly measured with the ICI. To discuss the helium abundance, and its variations, we use the helium density measured by the ICI, and refer it to the proton or electron density determined by the solar wind plasma instrument on the same spacecraft (Bame et al., (1978)). We thus obtain estimates of the relative abundance of helium with respect to hydrogen, to compare with previous work.

The ICI instrument, because of the characteristics of the stigmatic Wien filter, has an acceptance angle parallel to the spin axis of the spacecraft (maintained perpendicular to the ecliptic plane to $\pm$ 1/4 degree) of $\pm$ 8 degrees. The solar wind plasma instrument, Bame et al., (1978), has a larger acceptance angle ($\pm$ 20°) in the same direction. As a result the flux of helium ions can be cut off from the ICI by a deflection of the solar wind in the N-S direction, whereas such a cut off of proton flux from the solar wind plasma instrument almost never occurs. Thus, determinations of the helium abundance at times of large N-S deflections are lower limits, and this could introduce a bias in average values which we have investigated. Of course, the north-south deflections affect the fluxes of other minor ions measured by ICI, in the same way, so that abundances are not affected. North-south deflections predominantly occur in the interaction regions of high speed streams, and exceed eight degrees for only 13 percent of the total observing time; Roberts, private communication, (1988), see Fig. 11; overall, any effect of N-S deflections on the helium abundance is within the uncertainties of the measurement. Effects of deflection in the E-W direction are irrelevant because of the spacecraft spin. The long term average densities we quote are affected much less by N-S deflections of the solar wind than by other uncertainties, such as efficiency determinations for both instruments, which might perhaps be uncertain by ~20%. Individual values and short term averages of helium density in interaction regions may be considerably affected by deflection of the solar wind in the N-S direction.

During the period covered in this paper, the Los Alamos solar wind density data consist of proton densities, at the beginning, and electron densities during the later part. The proton densities n_p for the later part were accordingly derived from the electron densities n_e by using the relation $n_p = n_e - 2n_\alpha$, where n_α is the $^4He^{++}$ density determined by ICI.

We emphasize that relative abundance determinations using observations by two different instruments introduce uncertainties which do not apply to determinations made with a single instrument. For the abundance measurements made by ICI alone ([^{3}He]/[^{4}He], [O]/[He], [Ne]/[He], [Si]/[He] and [Fe]/[He]) there is no such problem. This is underlined by the excellent agreement between the ICI and the foil-determined abundances.

For the absolute [He]/[H] abundance determined by the combination of ICI and the Solar Wind Plasma instrument, it was necessary to reconcile the values obtained with standard previously measured values, taking into consideration the uncertainties in the calibration of the two instruments ($\pm$20% each). We have therefore multiplied the abundances by a constant factor of 1.25, which is within the expected limits, and there is no evidence that this number varied during the period.

Figure 12 and Table 3 show the ^{4}He abundance data for the period August, 1978 to December, 1978. Figures 13, 14, 15, and 16 are for the rest of the data set in the same format as that of Figure 12, covering six monthly intervals.

At the top left hand corner of each figure is a logarithmic flux contour plot; below are two normalized histograms of the distribution of the abundance ratio for the velocity ranges $300 \leq U \leq 450$ kms^{-1} and

$451 \leq U \leq 620\ kms^{-1}$ respectively. At the top right hand corner is a plot of the apparent variation of helium abundance with bulk speed. The error bars shown are the standard deviations of the means of the observations for the six month. The average abundance is a maximum at around the time of solar maximum (defined by sunspot number) as reported previously by Ogilvie and Hirshberg, (1974); Feldman et al., (1978).

Figures 12, 13, 14, 15, 16 also show clearly that there is an apparent dependence of the relative abundance of helium on solar wind speed which is most pronounced, as noted by Neugebauer, (1981), before and around solar maximum. Bame et al., (1977) suggest that the root cause of the velocity dependence is the frequent occurrence of very low abundances at times of low speed. It was from observations during the period 1971 to 1974, when solar activity was dropping to a minimum, that Bame et al., (1977) deduced the existence of a structure-free state in the solar wind at high speeds, associated with coronal holes, with a relatively constant value of helium abundance. We must emphasize that Bames "high speed" data set consisted of time intervals when the solar wind speed exceeded 650 kms^{-1} (mean value 702 kms^{-1}), well above the range of the ICI. Thus our observations are largely confined to the "low speed" wind regime as defined by Bame et al., (1977). Nonetheless, there are many examples of shocks and coronal-hole-associated flow in our data set. The split in the speed range at 450 kms^{-1}, adopted here, divides our observations into examples of the low speed wind and of medium speed wind. During the years 1978 to 1982, the solar wind speed exceeded the upper limit of the range of our instrument only 4% of the time. Thus we should expect to see many of the characteristics of the high speed flow in our upper velocity sample. In particular the data for 1982 show a rather narrow distribution of abundance around the mean value.

Figure 17, is a plot of the long term variation of Helium abundance during solar cycles 20 and 21; the ICI observations began in August, 1978. The observations made between 1962 and 1976 (solar cycle 20) described by Neugebauer, (1981) although showing a good deal of scatter definitely demonstrated a variation of $^4He^{++}$ abundance with solar activity. This is confirmed by the ICI results obtained between 1978 and 1982 during the period of the maximum of solar cycle 21. The two points plotted as crosses inside circles in Figure 17 were obtained from the first year of Voyager 2 measurements, while that spacecraft was reasonably close to Earth (Lazarus, private communication, 1988)). The variation of helium abundance during solar cycle 21 seems somewhat more peaked than that observed in cycle 20, and follows variations in the sunspot number fairly closely. A better measure of solar activity to compare with the abundance variation might be an index more closely related to the area of active regions. It seems that the higher abundances observed at active times largely arise because of increased frequency of emission of enriched material, presumably accumulated by fractionation in the lower corona.

In presenting $^4He^{++}$ abundance data for solar cycle 21 we have multiplied the values by a constant factor of 1.25 to join smoothly to the earlier observations. This factor is well within the combined uncertainties involved in the calibrations of the ICI and Los Alamos solar wind instrument which could be as much as 20% for each instrument.

As may be seen from the histograms near solar maximum, the helium abundance exceeds ten percent for an appreciable fraction of the time. These high abundance periods are often associated with enriched driver gas behind interplanetary shocks. Treatment of these events requires correction to take into account angular deflections perpendicular to the ecliptic plane, which can occur at the times of increases in helium abundance associated with shock flows, and this will be carried out in the future.

Conclusions

Analysis of four and one half years of almost continuous observations of the abundances of several ionic species in the solar wind leads to the following conclusions.

1). Oxygen and iron ions move with the helium rather than with the protons in the solar wind. When the helium ions are accelerated in high speed flows to a bulk speed greater than that of the protons, the other minor ions are also accelerated. There seems to be a tendency for the iron ions to lag slightly behind the helium at the highest speeds.

2). There is a strong tendency for the thermal speeds of the ions in the solar wind to be approximately equal, when the effect of collisions is negligible. This leads to the observation that $T_i \simeq$ Const. m_i.

3). Abundances of ^{3}He, ^{4}He, O, Ne, Si and Fe have been measured over time periods long enough and for conditions diverse enough to be fully representative of the solar wind. These abundances agree very well with those derived for similar species in Solar Energetic Particle events. Comparison with Solar System abundances shows that helium is under abundant and Si and Fe over abundant in the solar wind. The former discrepancy seems to be due to gravitational fractionation in the corona, and the latter to a mechanism, not fully understood, which links a low first ionization potential with a high probability of incorporation into the solar wind.

4). During solar cycle 21 we have observed the expected variation of the helium abundance with solar activity, combined with apparent dependence of the helium abundance on solar wind speed. Both of these effects result from variation in the occurrence rate of short term helium increases with solar activity and solar wind speed. The existence of the suggested "structure-free" solar wind, associated with coronal hole flow and a relative abundance narrowly distributed about a value of 0.04, is favored by this data set. A number of periods of high helium abundance were observed.

The ICI represents an importance advance over earlier instruments, and has made possible the determination of truly representative solar wind abundances for a small but important sample of ions. In the near future these results will be supplemented by measurements of charge and mass at higher resolution, to be carried out by the next generation of instruments.

Acknowledgments

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Figure Captions

Fig. 1a. Histogram of the ratio of the scalar speed difference between $^4He^{++}$ and H^+, ΔV, to the Alfven speed V_A for times when $^4He^{++}$ speed was between 300 and 400 km s^{-1}. The period covered was June 19 to September 7, 1979. Positive values of the ratio correspond to $V^4{}_{He}{}^{++} > V_H{}^+$. (From Ogilvie et al., (1982)).

Fig. 1b. Histogram of the ratio of the scalar speed difference between $^4He^{++}$ and H^+, ΔV, to the Alfven speed V_A for times when $^4He^{++}$ speed was between 400 and 500 km s^{-1}. The period covered was March 10 to November 2, 1979. Positive values of the ratio correspond to $V^4{}_{He}{}^{++} > V_H{}^+$. (From Ogilvie et al., (1982)).

Fig. 2. Histogram of the ratio of the speed diffrence between $^{16}O^{6+}$ and $^4He^{++}$ to the $^4He^{++}$ velocity for times when the $^4He^{++}$ speed was between 400 and 500 km s^{-1}. The period covered was March 10 to November 2, 1979. (From Ogilvie et al., (1982)).

Fig. 3. Histogram of differences between iron speeds and helium speeds. The average speed difference is 3 km/s, and the standard deviation of the distribution is 15 km/s. (From Schmid et al., (1987)).

Fig. 4. A plot of hydrogen and helium speeds in the solar wind on July 6 and July 7, 1979, showing the change in sign of the speed difference caused by the electrostatic potential difference across the interplanetary shock. The dashed line represents the helium speed and the solid line the hydrogen speed. (From Ogilvie et al., (1982)).

Fig. 5. Kinetic temperatures of $^4He^{++}$, O^{6+}, O^{7+}, and Fe as determined in the solar wind during two consecutive solar rotation periods with two recurring high-speed streams which correlate with elevated kinetic temperatures for ions investigated here. The iron temperatures are often more than 3×10^6 K, significantly above coronal temperatures. (From Bochsler et al., (1985)).

Fig. 14. Helium abundance data for the year 1980.

Fig. 15. Helium abundance data for the year 1981.

Fig. 16. Helium abundance data for the year 1982.

Fig. 17. Above - Variation of helium abundance during solar cycles 20 and 21. Early observations taken from Neugebauer (1981). Key: M2 - Mariner 2; V3-Vela 3; E34 - Explorer 34; O5-OGO 5; H1-Heos 1; E43 - Explorer 43; I-Imps 6 and 8. Later observations are from Voyager 2 and the present work, for which the normalization factor 1.25 has been used.

Below - Sunspot number for the same period as an indicator of solar activity.

Fig. 6. Contour plot of log (Flux $^3He^{++}$)) vs. log (Flux ($^4He^{++}$)). The contour levels are marked on the figure, and the results of five Apollo foil experiments are shown as dots labeled 11 through 16 (Geiss et al., 1972). The line corresponds to $^4He/^3He = 2000$. (From Coplan et al., (1984)).

Fig. 7. Correlation of oxygen fluxes with helium fluxes; the dashed lines are for He/O = 60, 80, 100. (From Bochsler et al., (1986)).

Fig. 8. Contour plot of log (Flux Ne) vs. log (Flux ^4He). The dots again refer to Apollo foil experiment results. (From Bochsler et al., (1986)).

Fig. 9. Contour plot of daily averages of log (Flux Si) versus log (Flux $^4He^{++}$). (From Bochsler, (1987)).

Fig. 10. Contour plot of daily averages of log (Flux (Fe)) versus log (Flux $^4He^{++}$). (From Schmid et al., (1988)).

Fig. 11. Data for the latitude angle of the solar wind direction for the year 1978, from the combined Imp 8, ISEE 3 data set from the NSSDC. Above - percentage of hour averages with latitude angle in the one degree angular range ending at the point shown.

Below - Integral of above latitude angle dependence.

Fig. 12. He abundance data for the period August 1978 to December, 1978. Top left, flux contour plot; Top right, apparent dependence of helium abundance on solar wind speed in km s^{-1}; Bottom left, normalized histogram of relative helium abundance for speeds below 450 km s^{-1} with mean value, number of hourly average observations, and mean for all speeds; Bottom right, normalized histogram of relative helium abundance for speeds above 450 km s^{-1} with mean value and number of hourly average observations.

Fig. 13. Helium abundance data for the year 1979.

TABLE I

	ISEE-3	SEP	
X	$[X]/[^4He]$	COOK	MCGUIRE
^3He	$(4.8\pm.5)\times10^{-4}$	------	------
^4He	1	1	1
O	$(1.3\pm.3)\times10^{-2}$	$(1.4\pm0.1)\times10^{-2}$	$(1.9\pm.2)\times10^{-2}$
Ne	$(1.8\pm.8)\times10^{-3}$	$(2.3\pm0.2)\times10^{-3}$	$(2.4\pm.3)\times10^{-3}$
Si	$(3.3\pm1.6)\times10^{-3}$	$(2.4\pm1.3)\times10^{-3}$	$(2.8\pm.3)\times10^{-3}$
Fe	$(2.5\pm1.5)\times10^{-3}$	$(2.7\pm.2)\times10^{-3}$	$(1.2\pm.2)\times10^{-3}$

TABLE II

ABUNDANCE WITH RESPECT TO HYDROGEN<

Element	Solar Wind (ICI)*	Solar System
H	1	1
^{3}He	$1.9\pm.2\times10^{-5}$	$2.3\pm1.2\times10^{-5}$[b]
^{4}He	$4.0\pm\times10^{-2}$[d]	$8\pm1\times10^{-2}$[c]
O	$5\pm1\times10^{-4}$	$7.4\pm1.5\times10^{-4}$[c]
Ne	$9.4\pm3\times10^{-5}$	$1.4\pm.5\times10^{-4}$[c]
Si	$1.3\pm.7\times10^{-4}$[e]	$3.6\pm.2\times10^{-5}$[c]
Fe	$1.1\pm.5\times10^{-4}$[e]	$3.3\pm.1\times10^{-5}$[c]

[a]Based upon $[^4He]/[H] = 5\times10^{-2}$.

[b]Hua and Lingenfelter, 1987; indirect photospheric measurement.

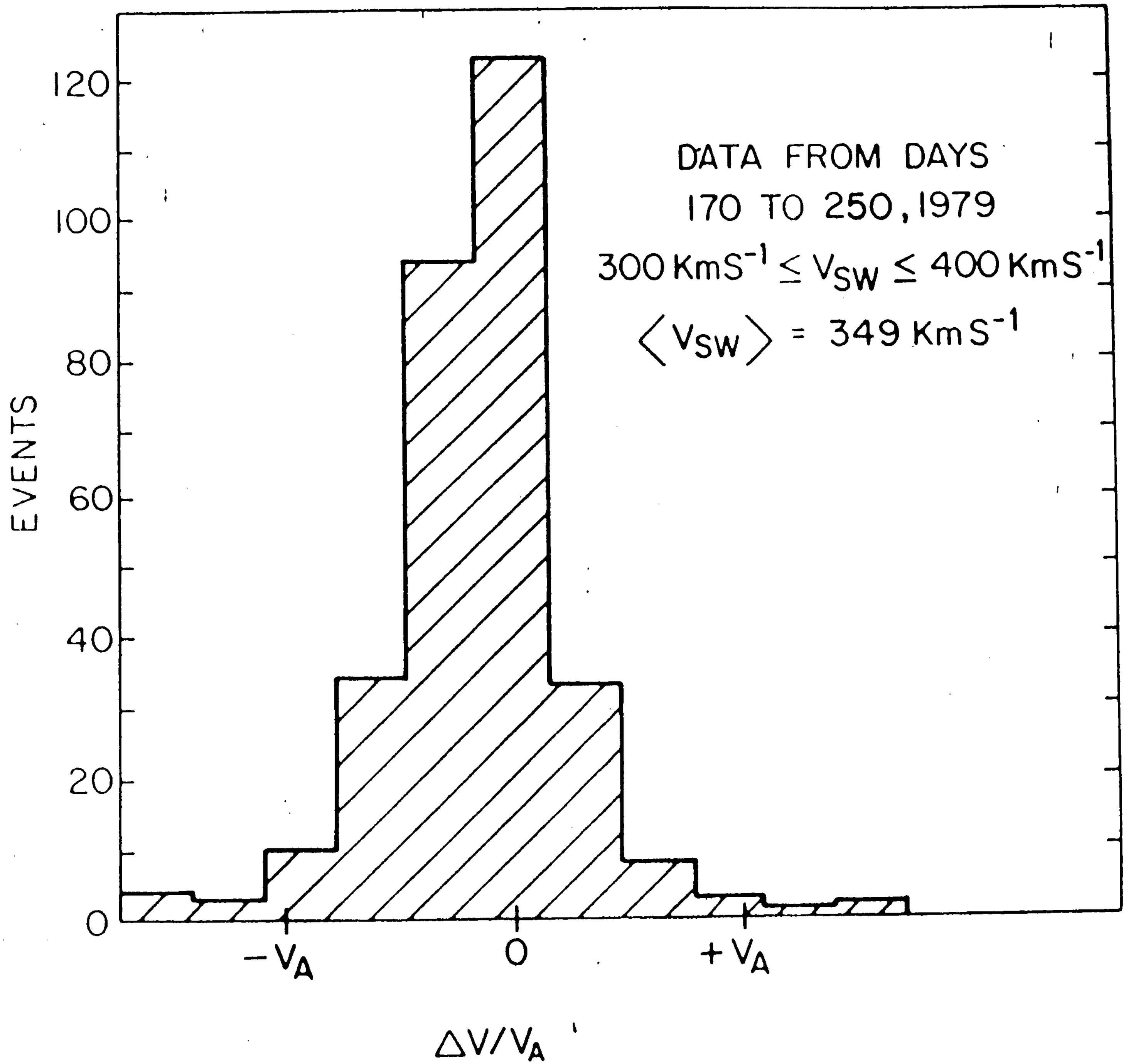
[c]From Anders and Ebihara, 1982.

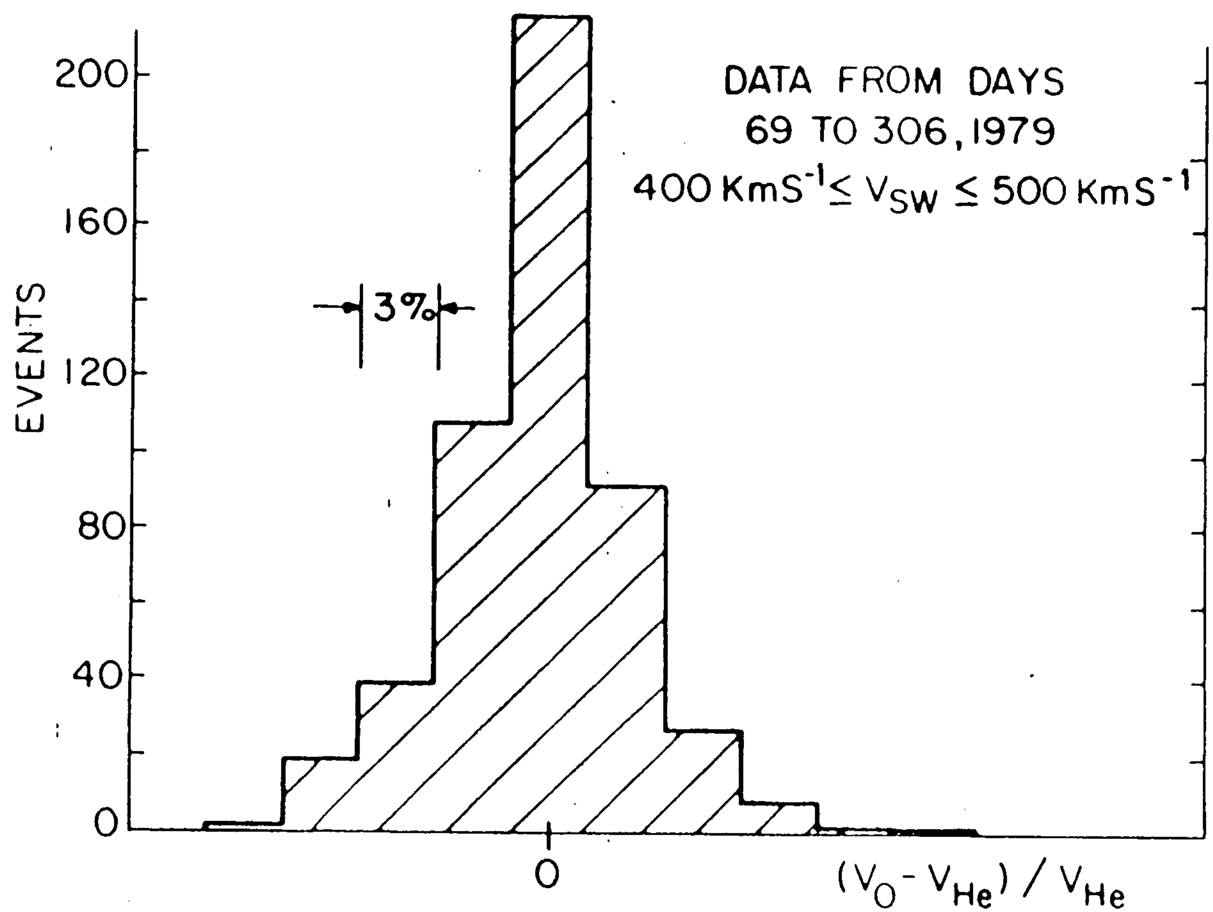
[d]Underabundant in the solar wind.

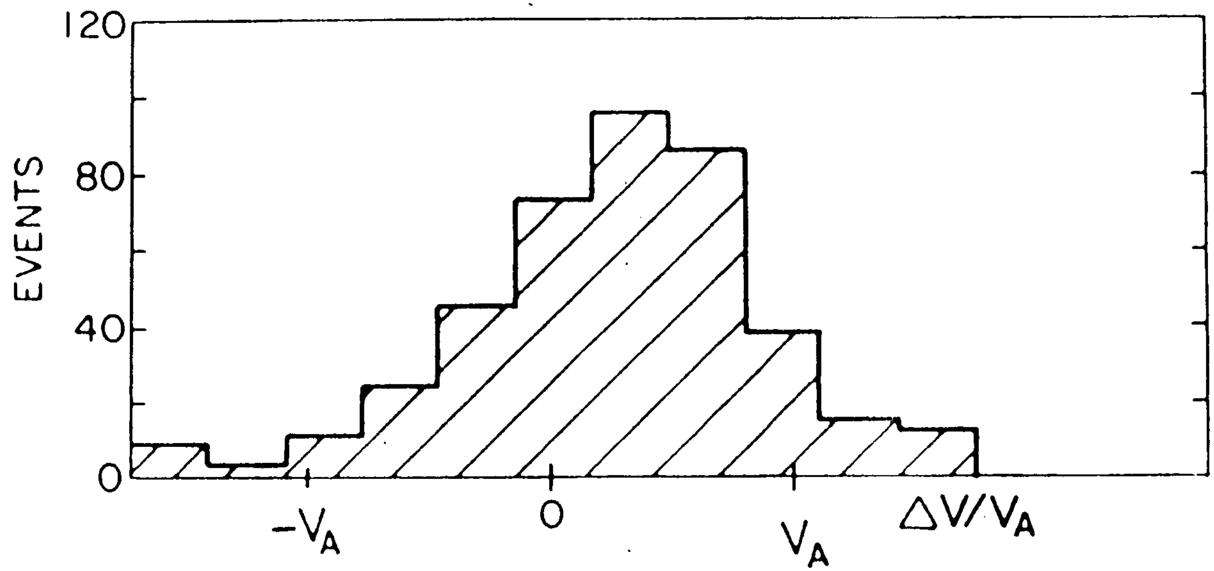
[e]Overabundant in the solar wind.

Table III

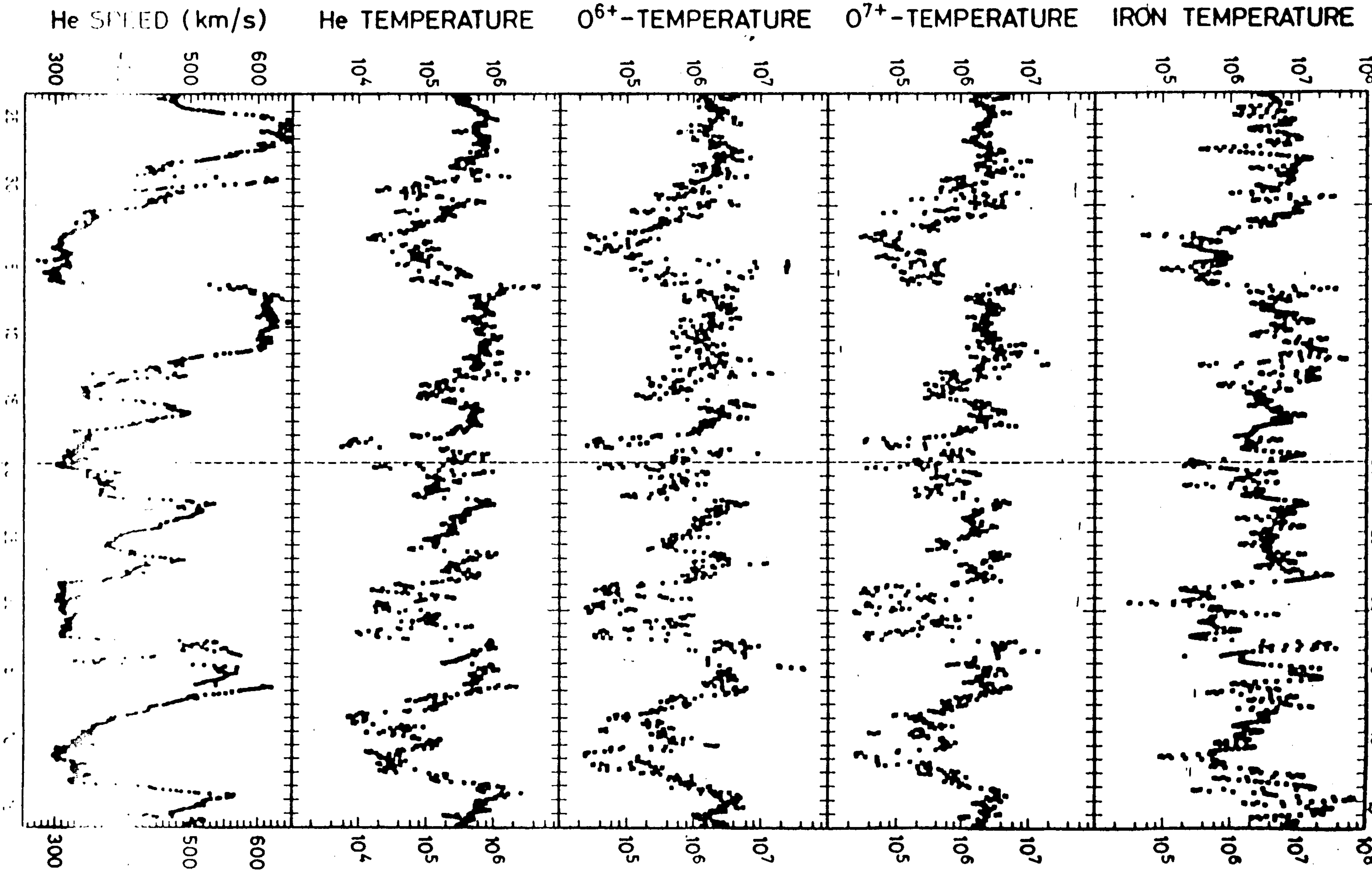
Period	Number of Observations	Average Abundance
Aug-Dec 1978	1793	.034
Jan-June 1979	2316	.047
July - Dec 1979	1918	.053
Jan-June 1980	2653	.037
July - Dec 1980	2080	.035
Jan-June 1981	2461	.041
July-Dec 1981	2902	.040
Jan-June 1982	2550	.035
July-Dec 1982	1258	.033
	19931 total observations	Ave .039

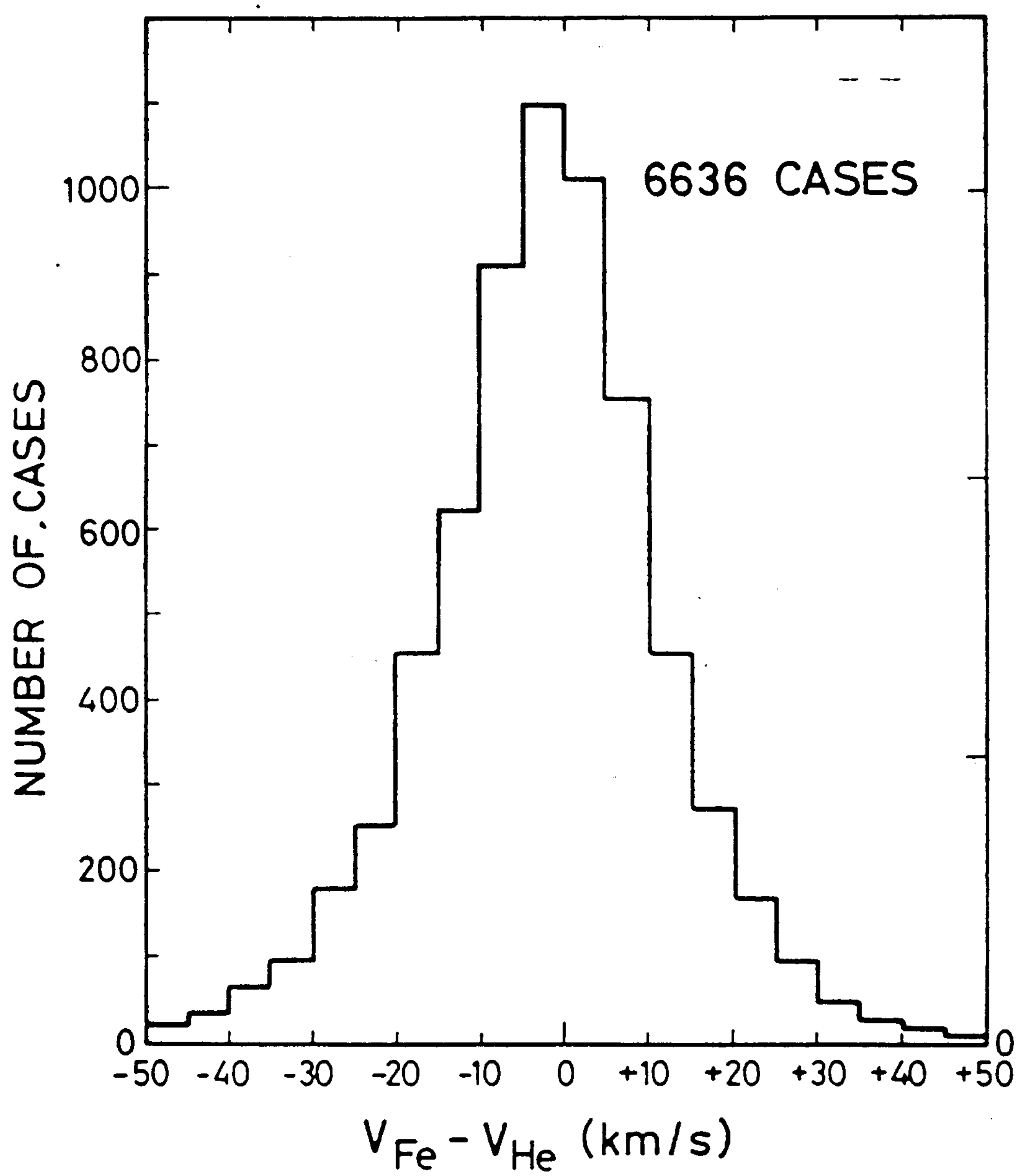

DATA FROM DAYS
170 TO 250, 1979
$300\ KmS^{-1} \leq V_{SW} \leq 400\ KmS^{-1}$
$\langle V_{SW} \rangle = 349\ KmS^{-1}$
EVENTS
120
100
80
60
40
20
0
$-V_A$
0
$+V_A$
$\Delta V/V_A$

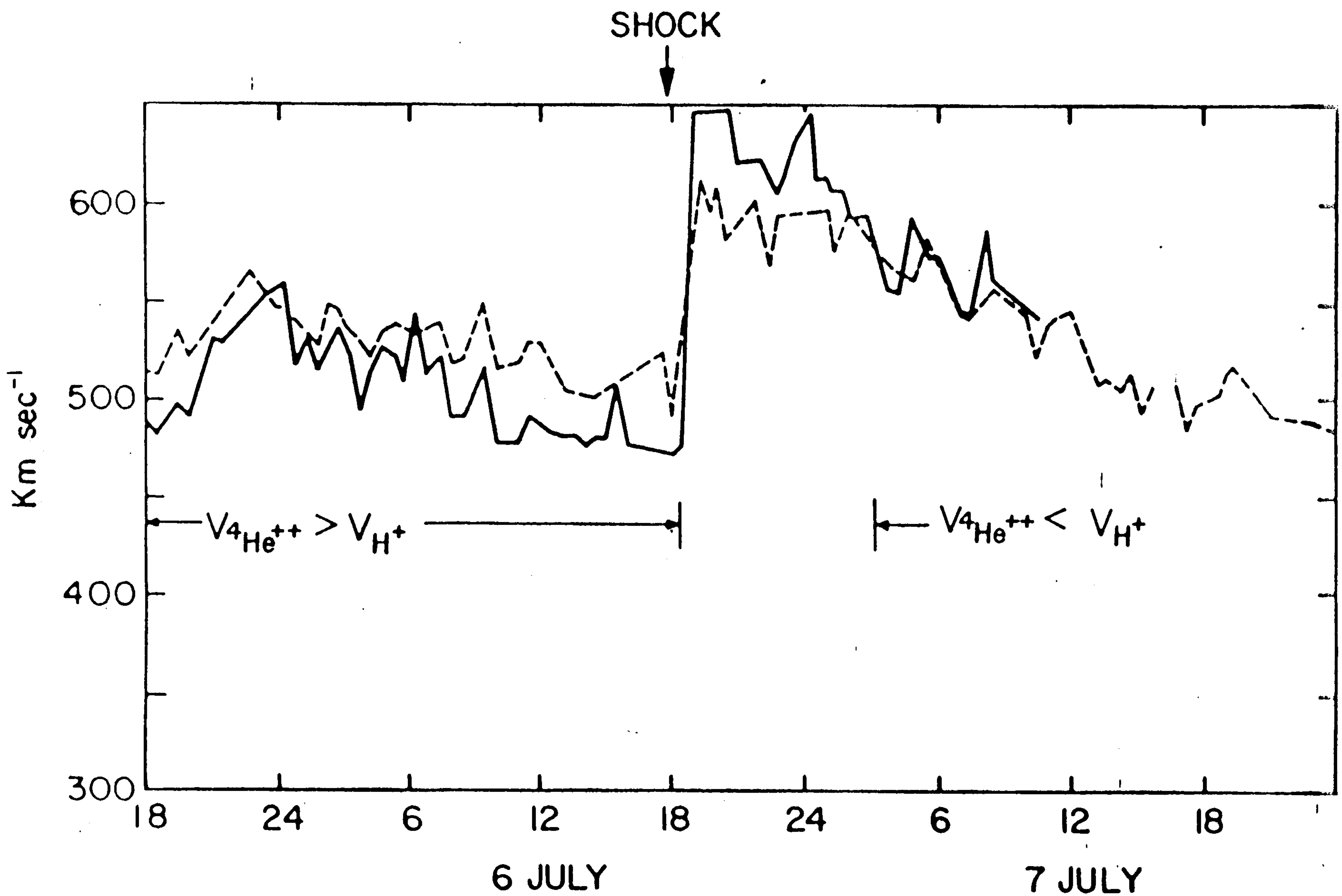

DATA FROM DAYS
69 TO 306, 1979
400 KmS⁻¹ ≤ V_SW ≤ 500 KmS⁻¹
3%
EVENTS
200
160
120
80
40
0
0
(V_O - V_He) / V_He

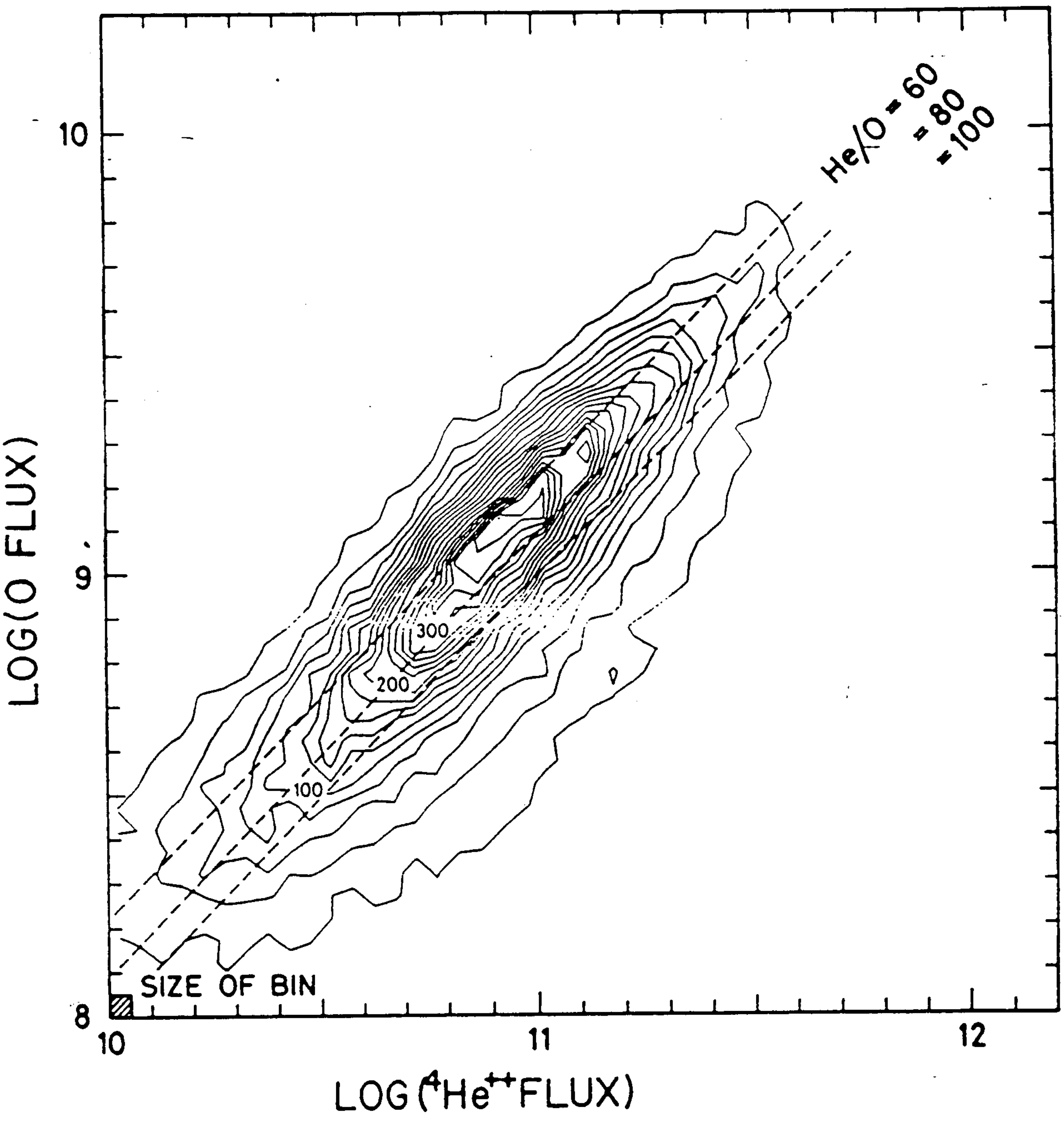


120
80
40
0
EVENTS
$-V_A$
0
V_A
$\Delta V/V_A$

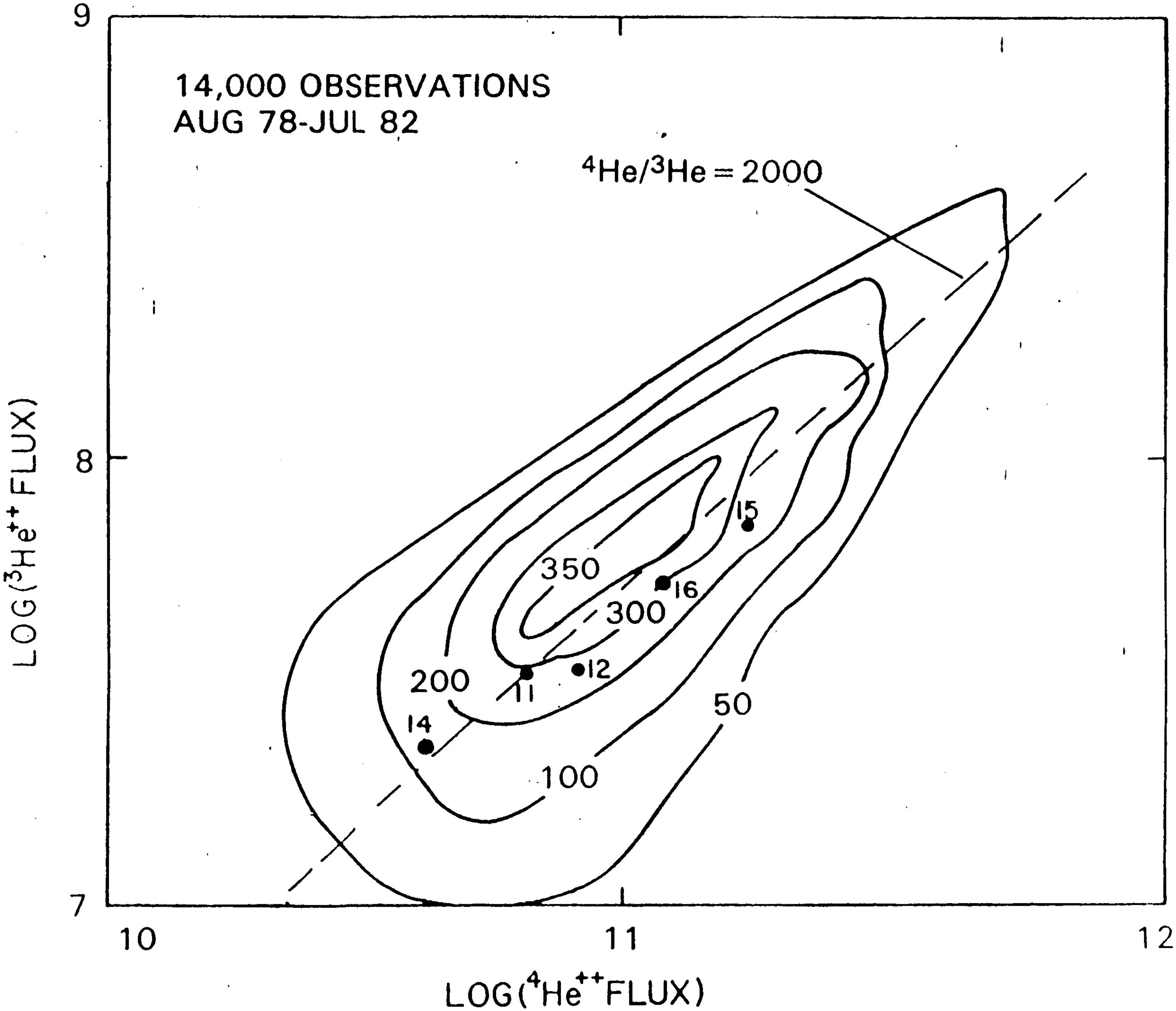

He SPEED (km/s)
He TEMPERATURE
O6+-TEMPERATURE
O7+-TEMPERATURE
IRON TEMPERATURE
300
500
600
10^4
10^5
10^6
10^7
10^8
25
30
5
10
15
20
25
30
5
10
15
MAY 1979
JUNE 1979


6636 CASES
NUMBER OF. CASES
0
200
400
600
800
1000
-50
-40
-30
-20
-10
0
+10
+20
+30
+40
+50
$V_{Fe} - V_{He}$ (km/s)

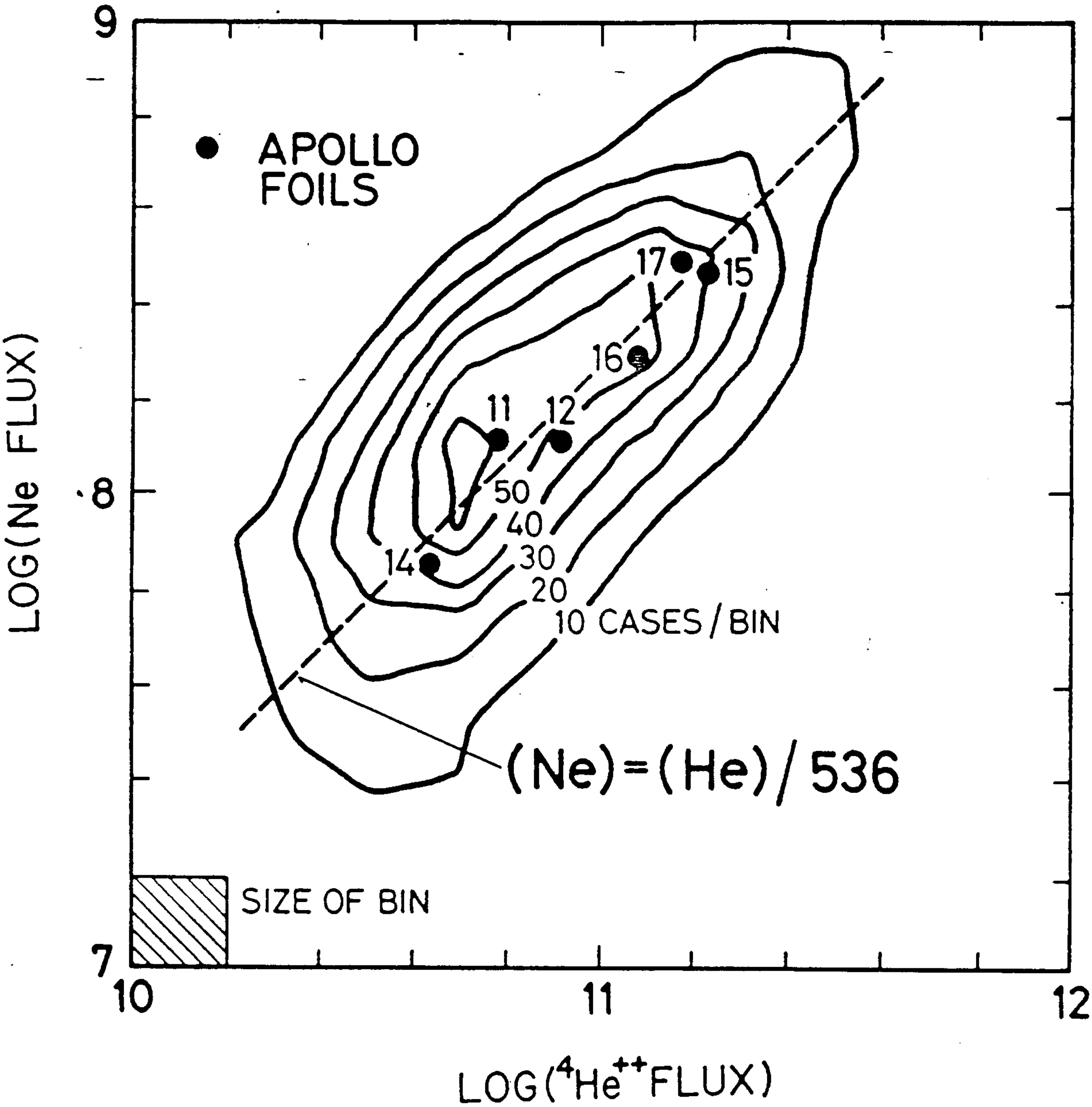

SHOCK
600
500
400
300
Km sec^{-1}
$V_{^4He^{++}} > V_{H^+}$
$V_{^4He^{++}} < V_{H^+}$
18
24
6
12
18
24
6
12
18
6 JULY
7 JULY

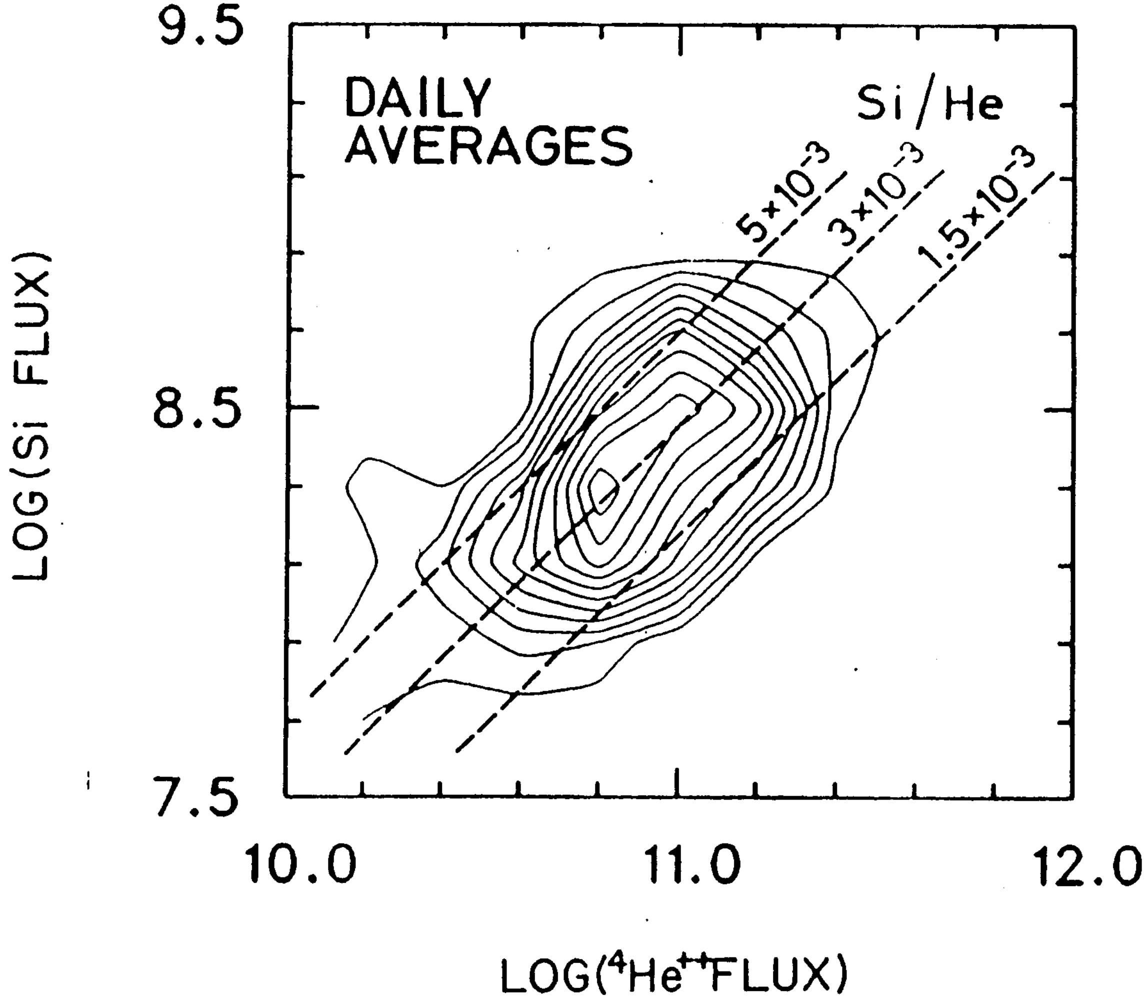


LOG(O FLUX)
10
9
8
LOG(⁴He⁺⁺FLUX)
10
11
12
He/O = 60
= 80
= 100
300
200
100
SIZE OF BIN

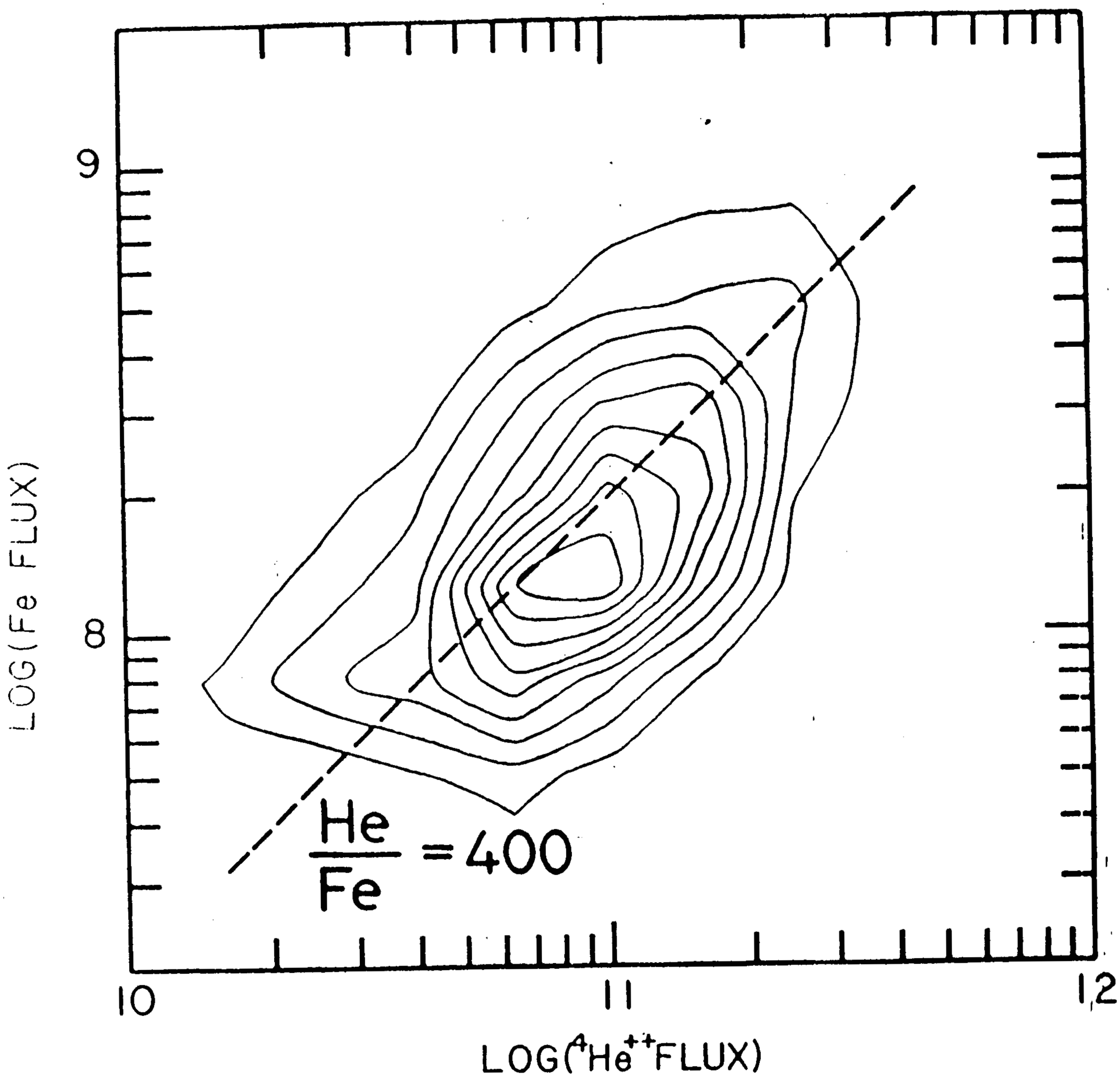


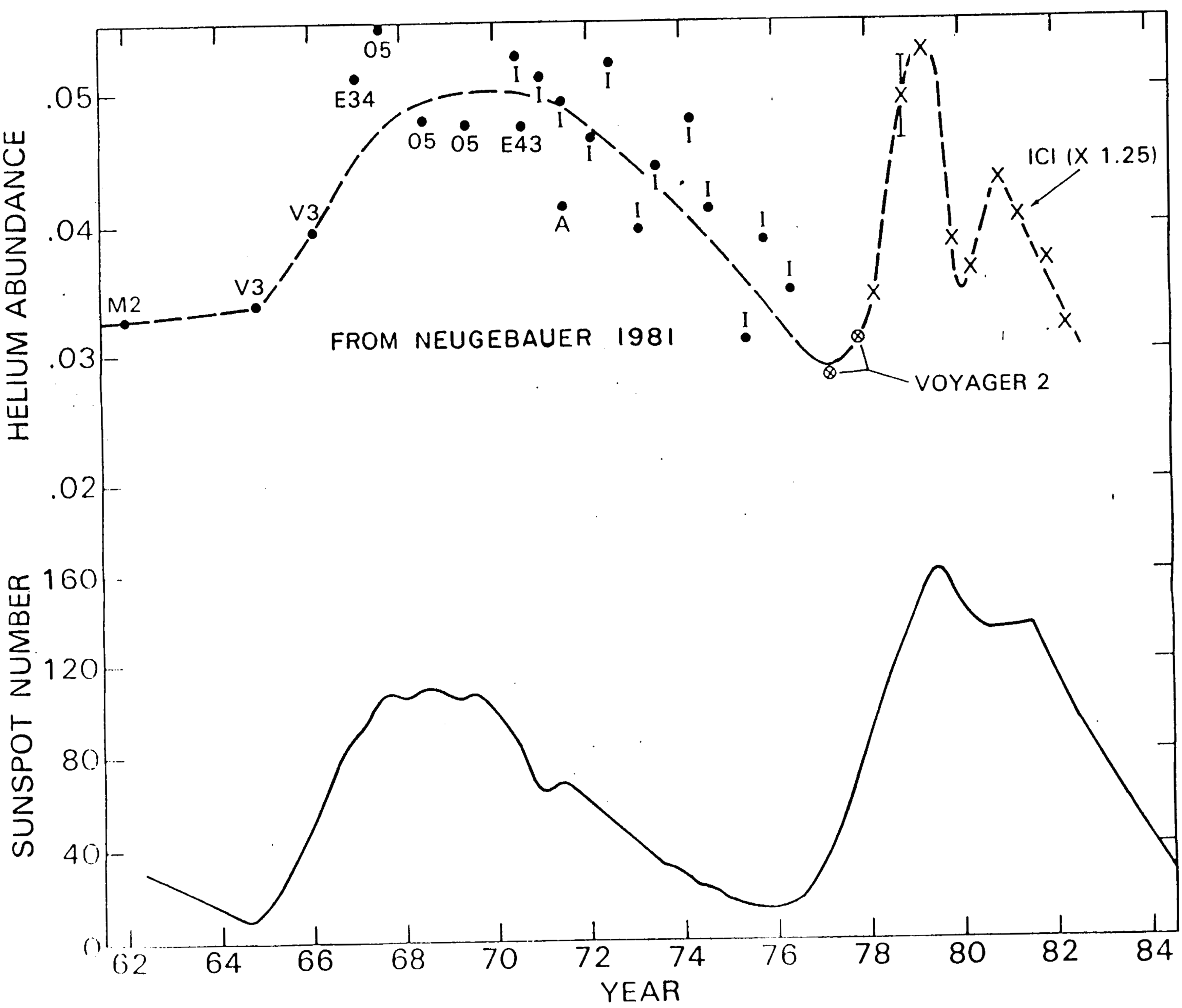
14,000 OBSERVATIONS
AUG 78-JUL 82
4He/3He = 2000
350
300
200
100
50
11
12
14
15
16
9
8
7
10
11
12
LOG(3He++ FLUX)
LOG(4He++FLUX)


9
8
7
10
11
12
APOLLO
FOILS
17
15
16
11
12
50
40
30
20
14
10 CASES / BIN
(Ne)=(He)/536
SIZE OF BIN
LOG(Ne FLUX)
LOG($^4He^{++}$FLUX)

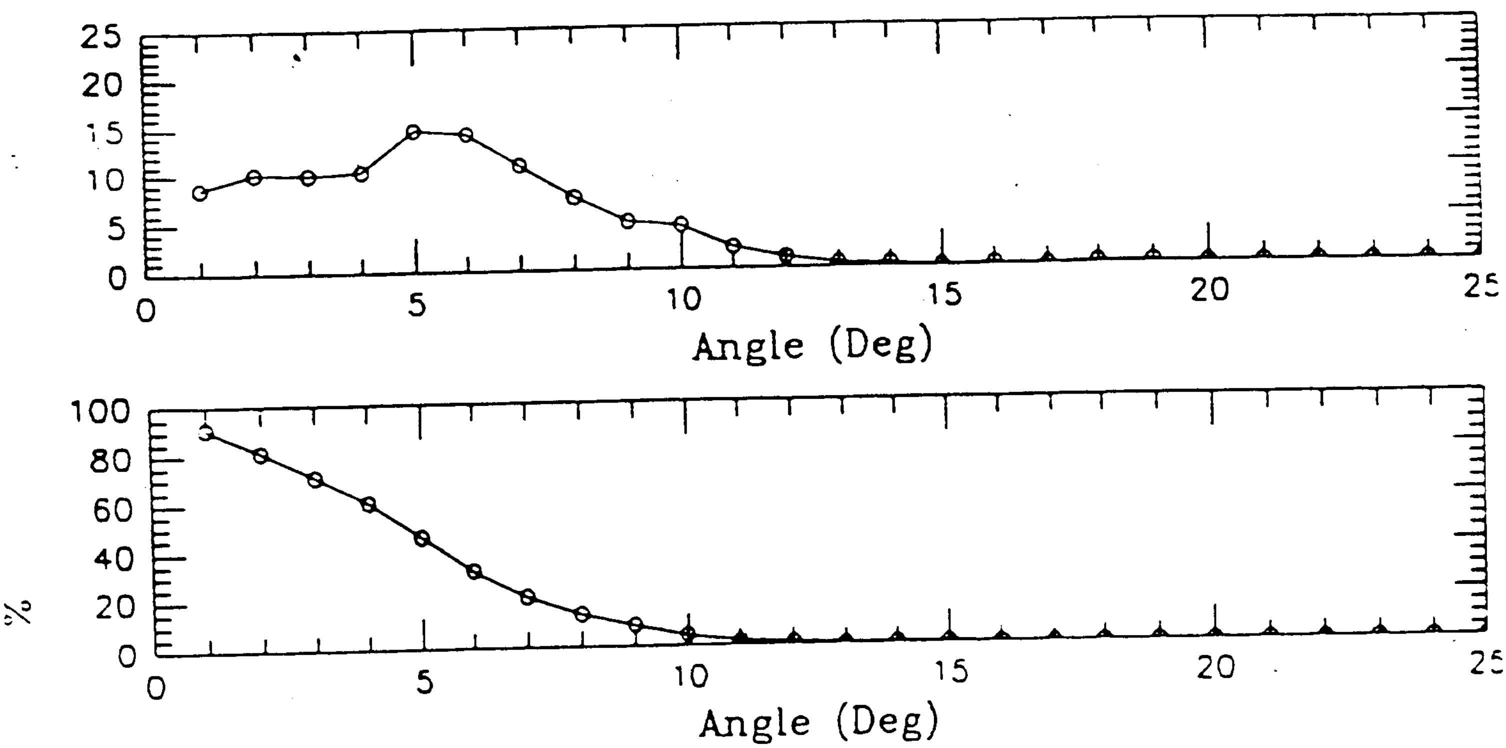


DAILY
AVERAGES
Si / He
5×10-3
3×10-3
1.5×10-3
9.5
8.5
7.5
10.0
11.0
12.0
LOG(Si FLUX)
LOG(4He++FLUX)

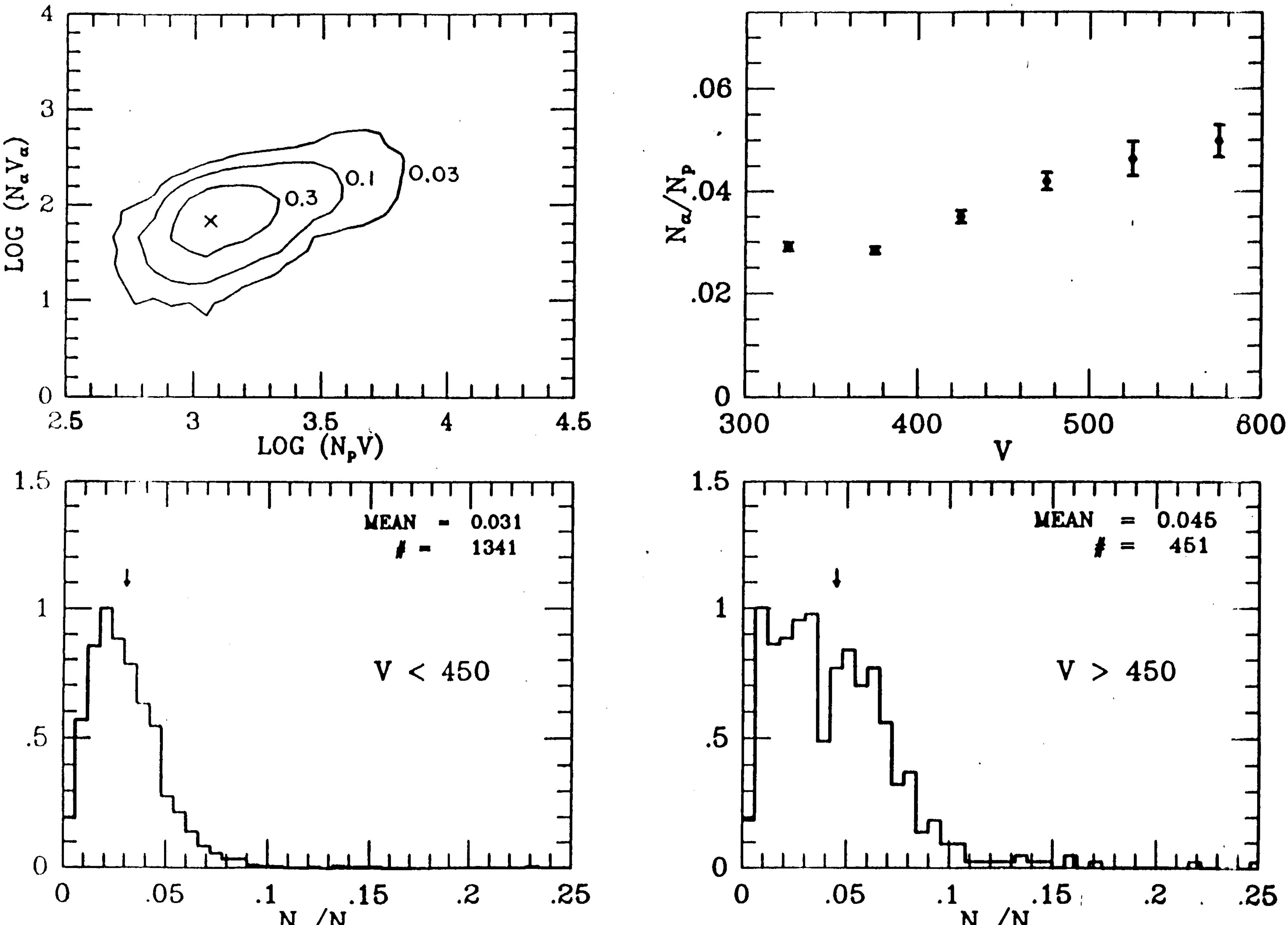

9
8
LOG(Fe FLUX)
He/Fe = 400
10
11
12
LOG(4He++ FLUX)



HELIUM ABUNDANCE
.05
.04
.03
.02
SUNSPOT NUMBER
160
120
80
40
0
62
64
66
68
70
72
74
76
78
80
82
84
YEAR
FROM NEUGEBAUER 1981
M2
V3
V3
E34
05
05
05
E43
A
VOYAGER 2
ICI (X 1.25)

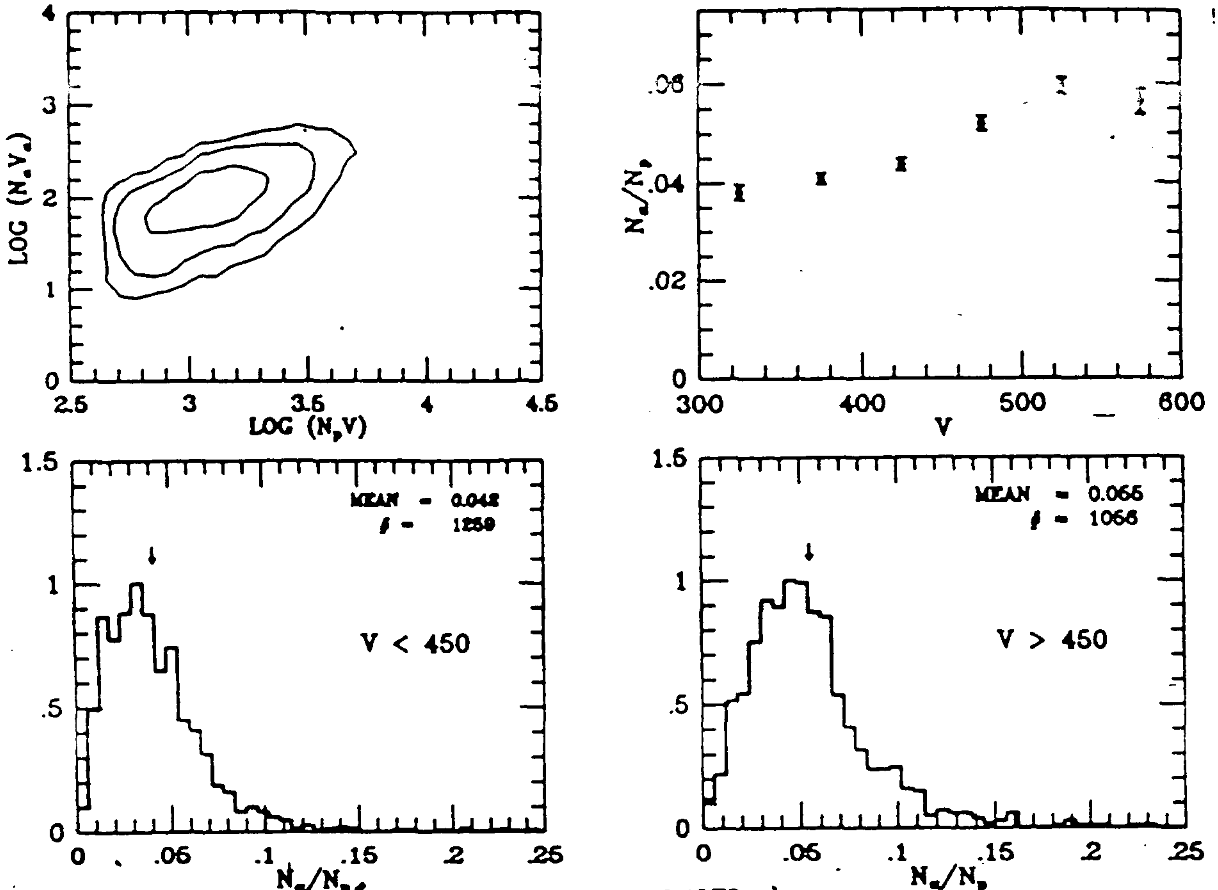


25
20
15
10
5
0
0
5
10
15
20
25
Angle (Deg)
100
80
60
40
20
0
%
0
5
10
15
20
25
Angle (Deg)

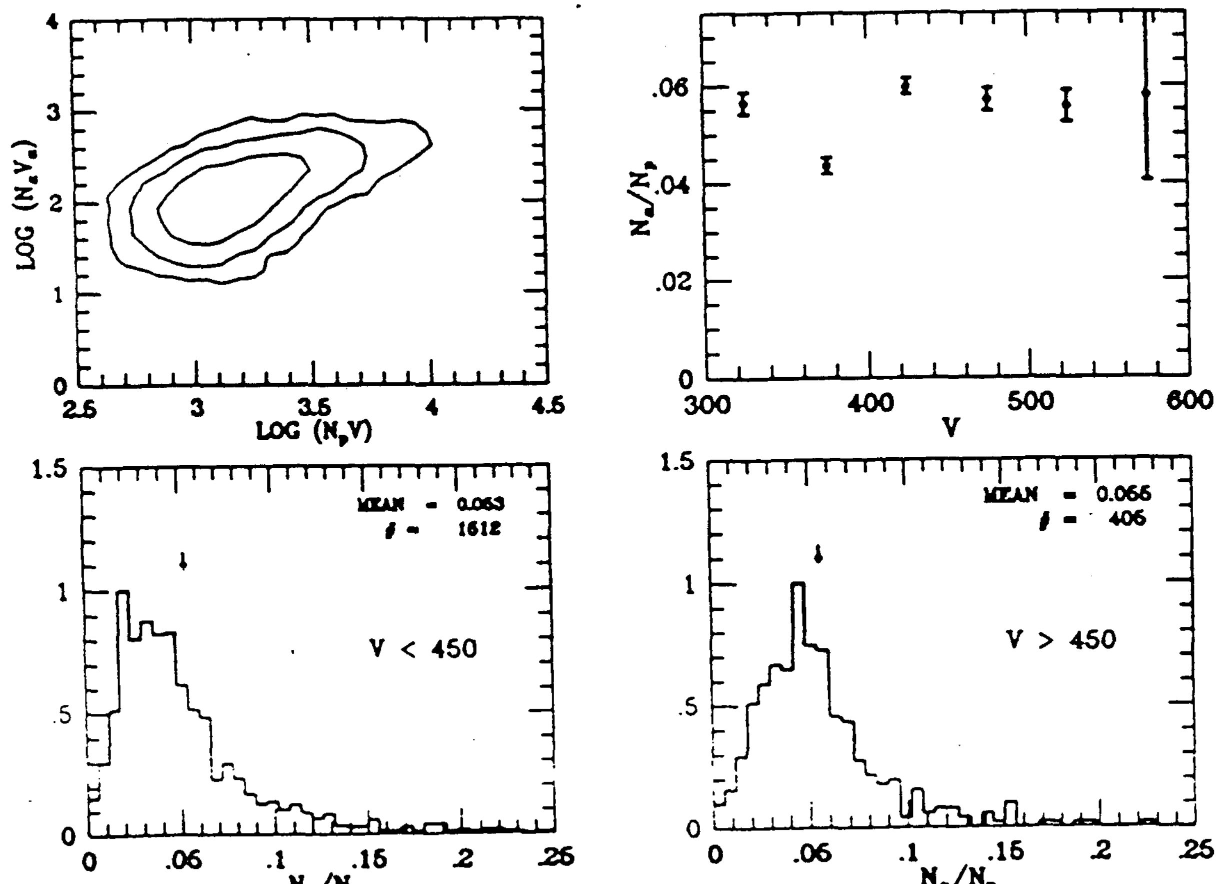


LOG ($N_\alpha V_\alpha$)
LOG ($N_p V$)
0.03
0.1
0.3
N_α/N_p
V
MEAN = 0.031
# = 1341
V < 450
N_α/N_p
MEAN = 0.045
# = 451
V > 450
N_α/N_p

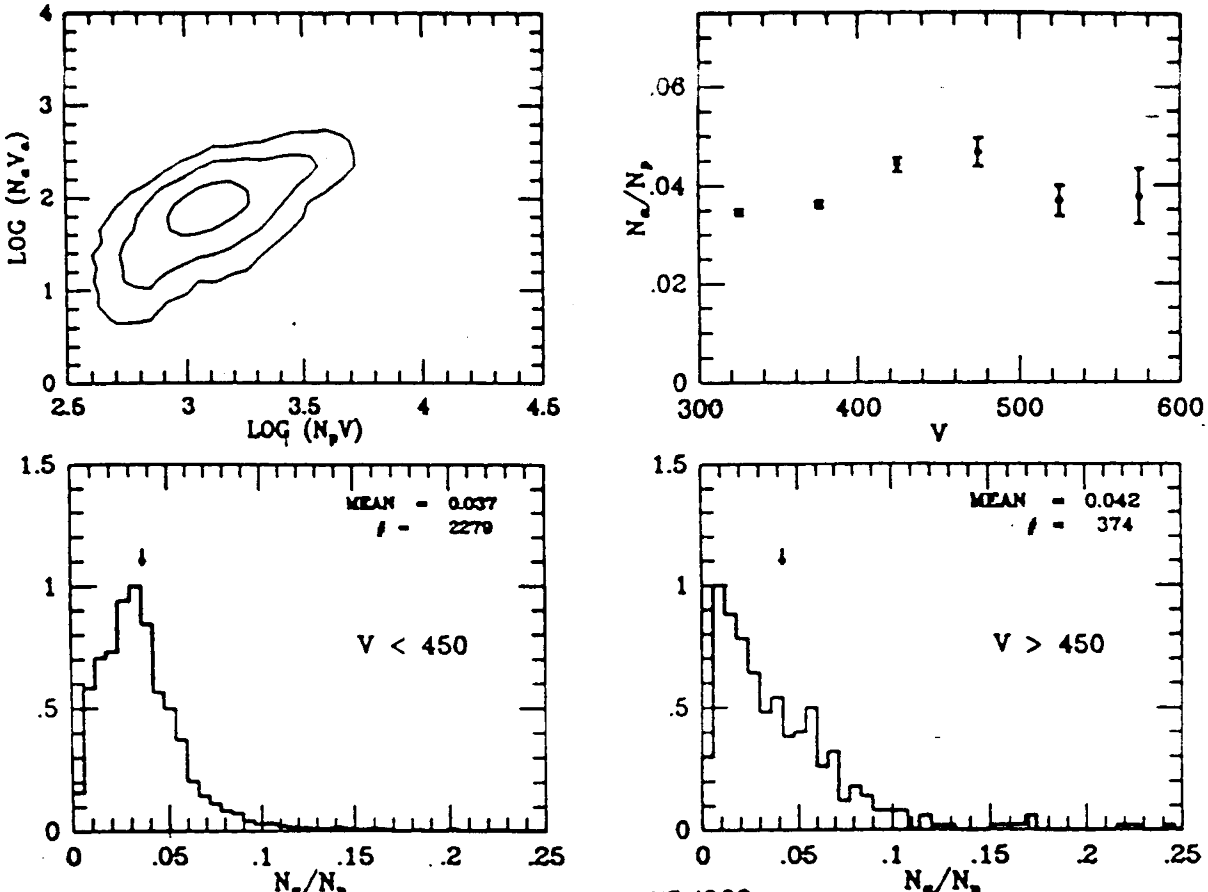
AUG - DEC 1978



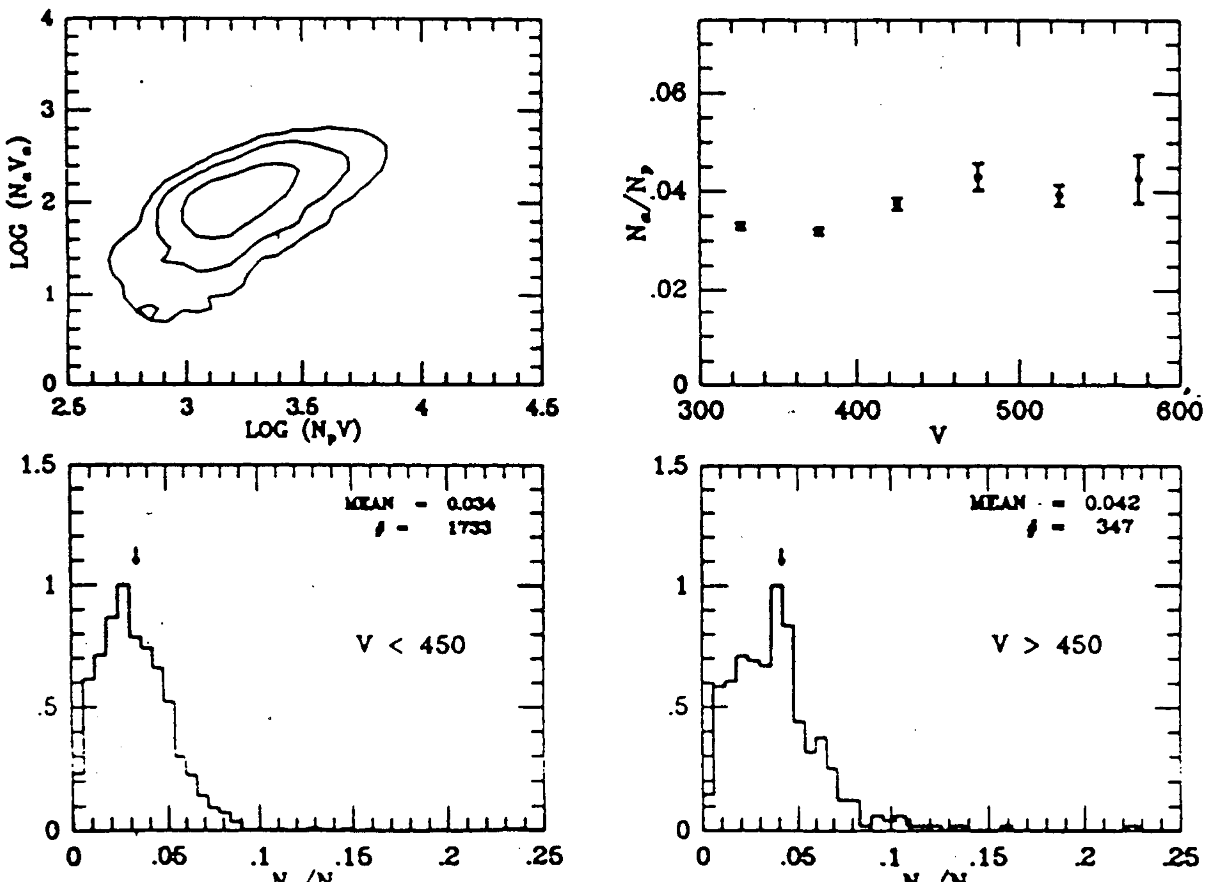
JAN - JUNE 1979



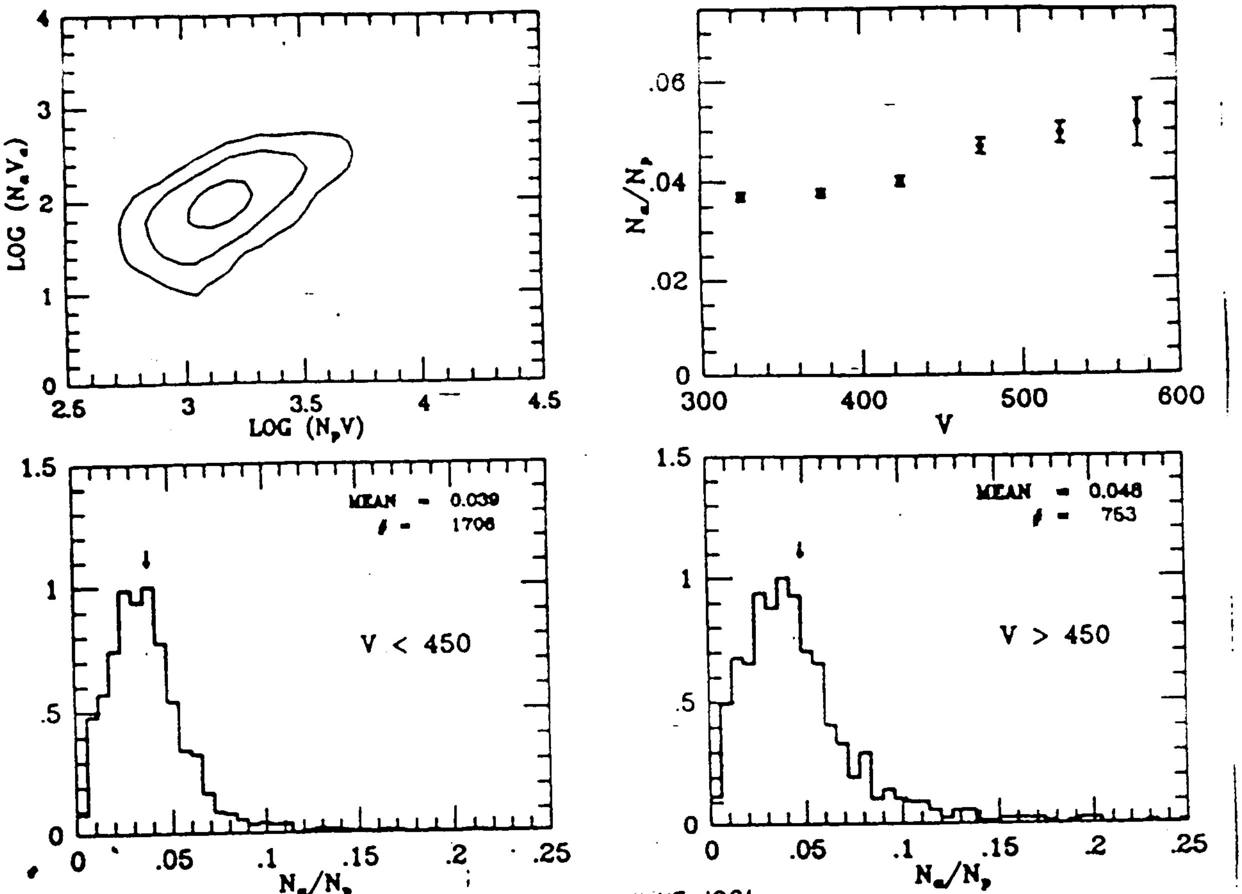
JULY - DEC 1979



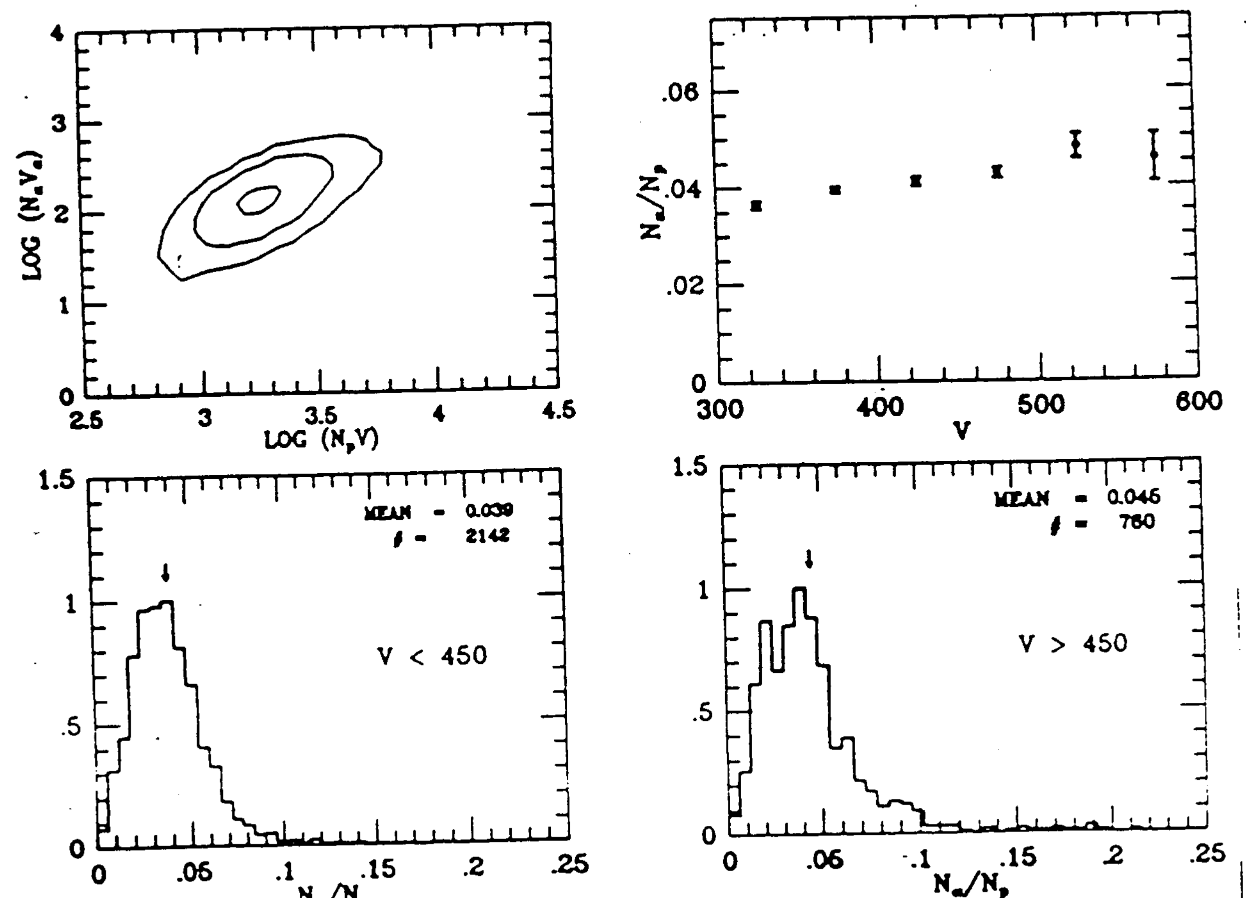
JAN - JUNE 1980



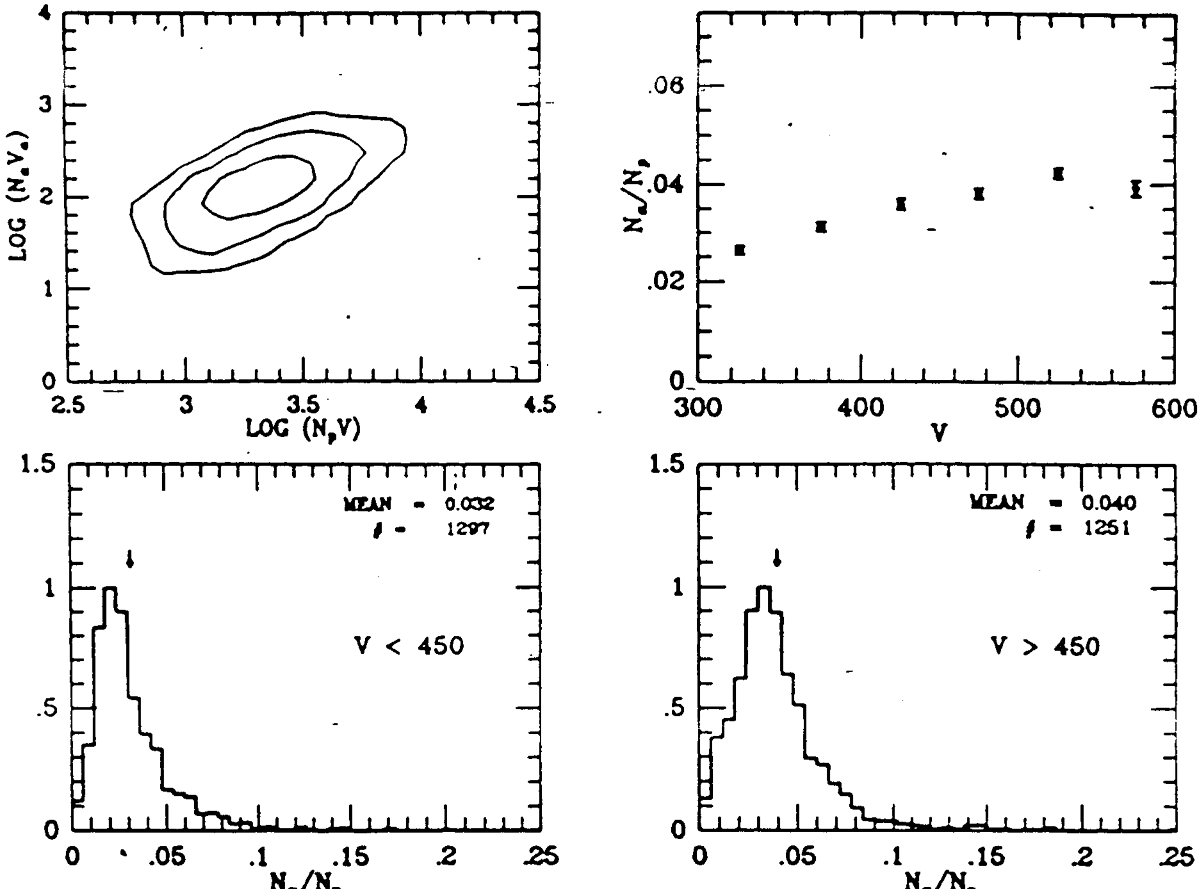
JULY - DEC 1980



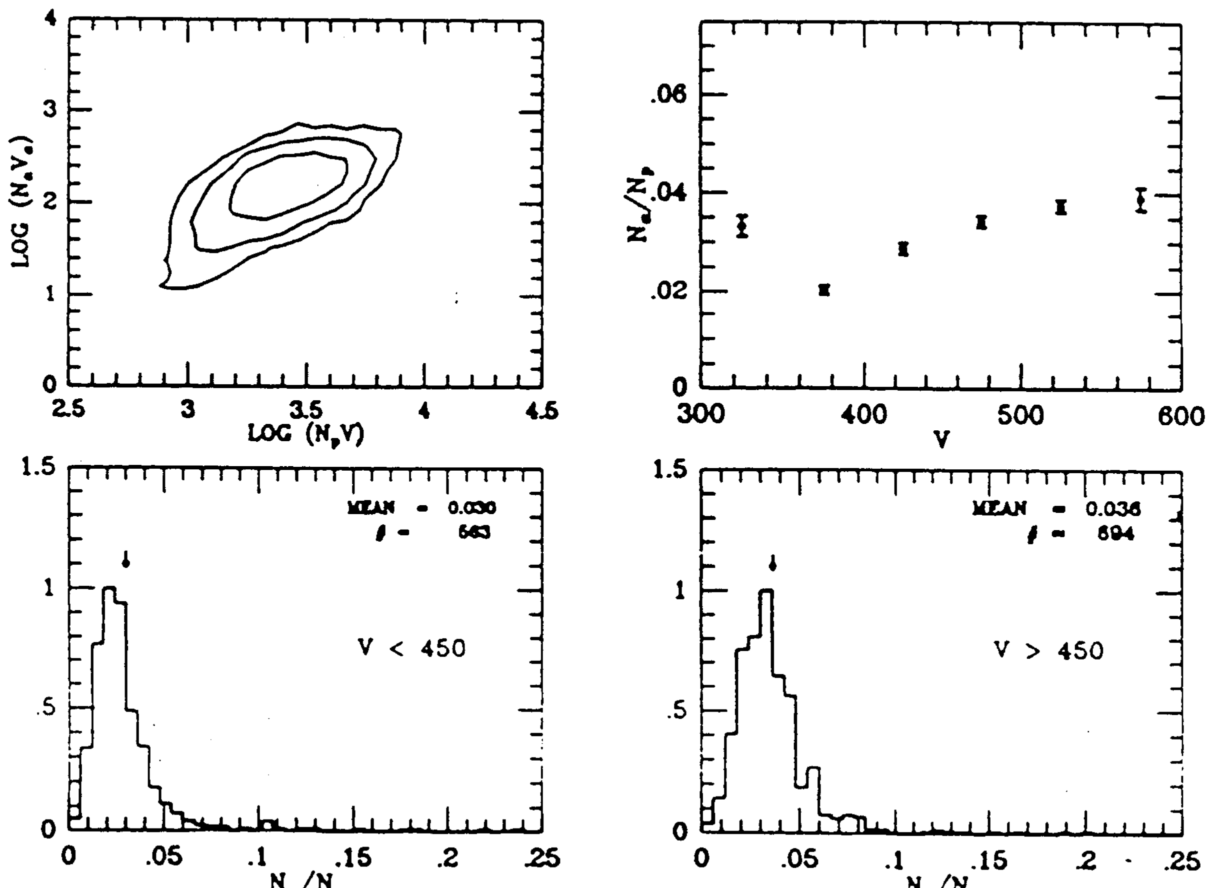
JAN - JUNE 1981



JULY - DEC 1981



JAN-JUNE 1982



JULY-DEC 1982

APPENDIX IV