THE RELATIVE ABUNDANCE OF $^3HE^{++}$ IN THE SOLAR WIND

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ABSTRACT

Continuous measurements of solar wind $^3He^{++}$ and $^4He^{++}$ from August, 1978 to December, 1981 have been made covering a full range of solar wind conditions. The average flux ratio <R> derived from these data is 2310 ± 50, in excellent agreement with the Apollo foil measurements. A probable correlation between <R> and solar activity has been found; however, an examination of the data during periods of $^3He^{++}$-rich solar flares shows no detectable increase in $^3He^{++}$ in the solar wind.

Introduction

Measurements of $^4He^{++}$ in the solar wind since its first discovery there (Neugebauer and Snyder, 1966) have shown its abundance to be highly variable, however the reason for this variability is not fully understood. Information about conditions in the source region can in principle be obtained by studying the abundance of $^3He^{++}$ relative to that of $^4He^{++}$. Since the only difference between the isotopes is their mass (ionization potentials and charge being identical), changes in their relative abundances may prove to be a sensitive probe of the acceleration and mixing processes operating in the source region. Furthermore, the low abundance of $^3He^{++}$ relative to protons (approximately 1:40,000) means that it can be considered as a true test particle in the solar wind.

Up to now, studies of $^3He^{++}$ in the solar wind were limited to periods of low solar wind velocity when the kinetic energy distribution of the dominant solar wind protons was sufficiently narrow so as not to interfere with observations of $^3He^{++}$. The ISEE-3 Ion Composition Instrument (ICI), launched in August 1978, has overcome this limitation by employing velocity as well as energy analysis (Coplan et al., 1978) with the result the $^3He^{++}$ abundances have now been measured continuously over the full range of solar wind conditions for more than four years.

In a previous publication (Ogilvie et al., 1980a) we presented a preliminary account of observations made between August and November, 1978 and March and August 1979. During this period the average $^4He^{++}/^3He^{++}$ abundance ratio <R> was reported to be $2.1 \pm 0.2 \times 10^3$, in excellent agreement with measurements made by the foil method (Geiss et al., 1972). In this paper we present results derived from a data set covering the period August 1978 to December, 1981. This period includes the maximum of solar activity cycle 21 which occurred in 1980, as well as the occurrence of a number of $^3He^{++}$-rich solar flares. Here we will concentrate on the variation of <R> with solar activity and correlations between $^3He^{++}$ in the solar wind and flares. A more comprehensive analysis will appear elsewhere.

Experimental Method and Data Reduction

The ICI has already been described by Coplan et al. (1978). The instrument obtains mass per charge (M/Q) spectra over the range of 1.4 to 5.6 with a resolution of 30, as long as the solar wind speed is between 300 and 620 km/s. Time resolution is 15 or 30 minutes depending on the operating mode. The raw data have been corrected for background (approximately 0.3 counts/sec per observation) which is primarily due to penetrating high energy particles which excite the detectors directly. The background is determined separately for each spectrum by monitoring a part of the M/Q-V matrix in which no solar wind ions appear. During solar particle events the background increases by an order of magnitude and spectra obtained during these periods have been deleted from the data set.

The $^4He^{++}/^3He^{++}$ abundance ratio is obtained from the corrected data by first fitting a convected Maxwellian velocity distribution function to the $^4He^{++}$ data taking into account the instrument function. The results of the fitting procedure are values for the velocity, kinetic temperature, density, and flux of $^4He^{++}$. Because of the small number of $^3He^{++}$ counts, a completely independent determination of the $^3He^{++}$ distribution function is not practical. The velocity of $^3He^{++}$ is taken equal to that for $^4He^{++}$ and the $^3He^{++}$ kinetic temperature is set equal to 3/4 that for $^4He^{++}$ (Ogilvie et al., 1980b). The $^3He^{++}$ density and flux are then calculated from the total corrected $^3He^{++}$ counts, using the instrument function and the values of velocity and temperature. The uncertainty in the ratio of $^4He^{++}/^3He^{++}$ flux, or density, R depends principally on the statistical uncertainty in the number of $^3He^{++}$ counts (typically 14 counts per observation). Errors associated with the assumed $^3He^{++}$ temperatures and velocities are expected to be small because the density is a rather weak function of these parameters. Figure 1 shows a plot of $^4He^{++}$ flux, $^3He^{++}$ flux and R for the

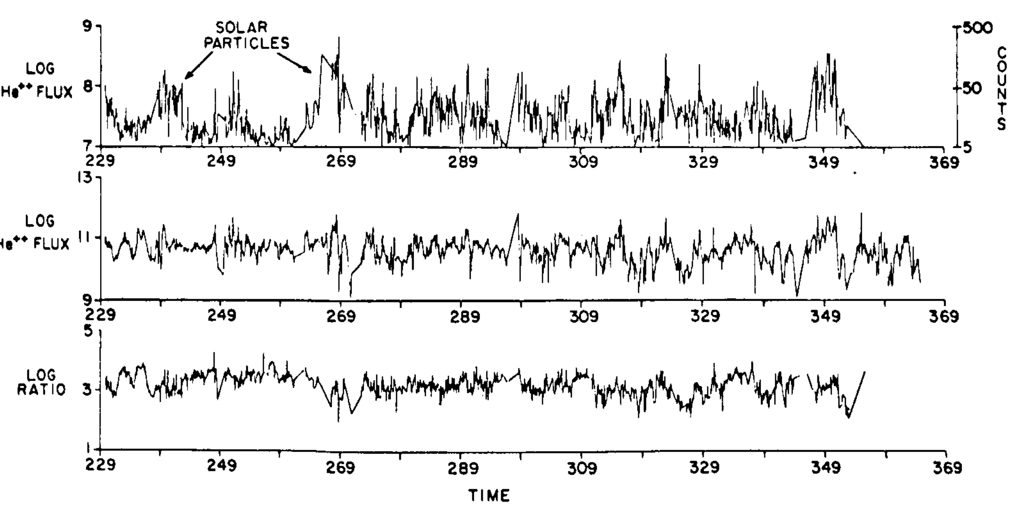

Figure 1. $^3He^{++}$ flux, $^4He^{++}$ flux and $^4He^{++}/^3He^{++}$ flux ratio as a function of time for the period 16 August 1978 to 27 December 1978. The data are hourly averages. The units of flux are particles $m^{-2}s^{-1}$.

period 18 August to 27 December, 1978. Hourly averages are shown and data gaps are crossed by straight line segments. Superposed on the high frequency statistical fluctuations of $^3He^{++}$ flux are lower frequency fluctuations which correlate well with the fluctuations in $^4He^{++}$ flux, for which the statistical accuracy is a few percent. The calculated overall correlation coefficient for the two fluxes for the complete data set is 0.65 indicating that the fluctuations in $^3He^{++}$ flux are generally physically significant, representing real changes in the $^4He^{++}/^3He^{++}$ abundance ratio.

Results

Figure 2 is a histogram showing the distribution of values of R, based on the complete data set. The most probable value, R_{MP}, corresponding to the maximum in the histogram, is ~ 1500. The average value, $\langle R \rangle$, is 2310 ± 50 and is obtained by summing the $^4He^{++}$ fluxes and dividing by the sum of the $^3He^{++}$ fluxes. This method for obtaining $\langle R \rangle$ gives a value which can be directly compared with the abundance ratio obtained by the foil technique in which the helium isotopes trapped by the exposed foil over a period of time are desorbed by heating and measured in a mass spectrometer. The agreement between the results of the two methods is excellent. Note that this method for calculating $\langle R \rangle$ is different from an average obtained by summing individual R values and dividing by the number of values. We estimate the signal-to-noise ratio for an individual measurement to be 2 at R = 3000. Thus, observed increases of R above ~

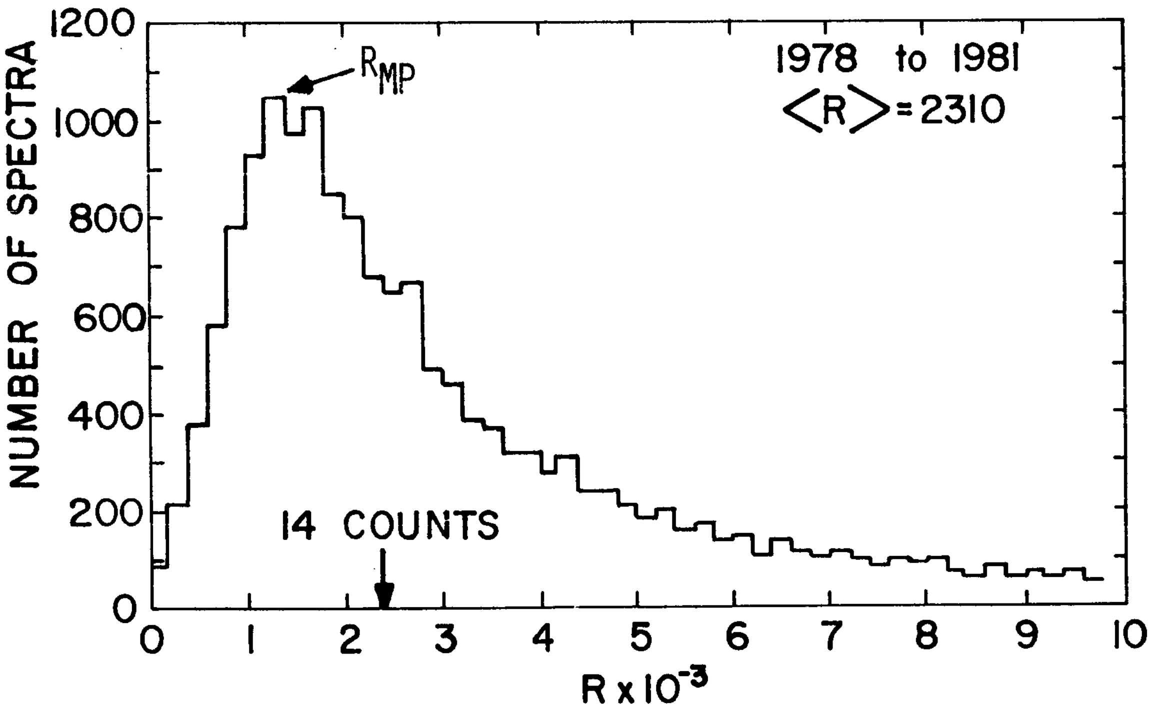

Figure 2. Histogram of $^4He^{++}/^3He^{++}$ flux ratios, R. The most probable, R_{MP}, as well as the average value, $\langle R \rangle$, of R are indicated. A value of R corresponding to $\langle R \rangle$ represents approximately 14 $^3He^{++}$ counts.

5000 which usually represent real physical changes in the abundances, are not well determined. Values of R well below <R> occur with considerable frequency, however the persistance of low R values for longer than about 6 hours is rare in our data. This is in contrast with the observations of Grünwaldt (1976) who reported R $\sim$ 540 for a period of 48 hours coinciding with a particularly low solar wind speed. Inspection of Figure 1 shows that such a low ratio is not particularly rare, but 48 hours is a long period for such a deviation from the most probable value to persist.

To further examine the relation between R and solar activity we have divided the data set into six-month intervals. The maximum of solar cycle 21 occurred in 1980 and from the data in Table I one can see that <R> for 1980 is 2465 $\pm$ 60 which is to be compared with 2310 $\pm$ 50 for the entire data set. Since the two averages differ by more than three standard deviations it is reasonable to conclude that events giving rise to large values of R in the solar wind are more prevalent around solar maximum than at other times. Values of R_{MP} for the six-month periods are also included in Table I.

TABLE I

$^4He/^3He$ Ratios

Period	Number of Days	< R >	R_{MP}
Aug. 18 - Dec. 31, 1978	136	2320	1600
Jan. 1 - June 30, 1979	180	2180	1600
July 1 - Dec. 31, 1979	184	2420	1600
Jan. 17 - June 30, 1980	164	2480	1200
July 1 - Nov. 27, 1980	149	2550	1600
Feb. 19 - June 30, 1981	131	2220	1600
July 1 - Oct. 18, 1981	109	2300	1700
Average 1978 - 1981		2310 $\pm$ 50	
Average 1980		2465 $\pm$ 60	

Among other sources of $^3He^{++}$ variability we have investigated a possible connection between ^{3}He-rich solar flares and solar wind $^3He^{++}$. The solar flares of interest are small but result in up to a thousand fold enhancement of $^3He^{++}$ at MeV/nucleon energies lasting for a few days (Reames and von Rosenvinge, 1981). Using a list of $^3He^{++}$ fluxes in the energy range from 1.3 to 1.7 MeV/nucleon kindly supplied by Reames (private communication, 1982) we selected seven ^{3}He events for which there was no coincident solar proton enhancement. If t_i is the time of observation of energetic particles during the i^{th} event, plasma emitted by the sun at the same time will arrive at 1 AU at about t_i+3 days. A superposed epoch analysis was performed to obtain <R(L)>, where <R> is computed over a period of two days, and L is a variable lag time, taking the values -4, -3,..., +4 days.

If the processes responsible for the enhancement of ^3He at MeV/nucleon energies also enhanced $^3He^{++}$ in the solar wind, we would expect a decrease in <R> at zero time, corresponding to a transit time of 3 days. Figure 3 shows the result; although there is a small decrease in <R> at about the expected lag, it is less than the standard deviation of the observations. The data are consistent with the emission by the sun of about 10% more ^3He than usual. Although estimates show this is not energetically impossible, we conclude that we did not detect increased ^3He in the solar wind at the time of these flares.

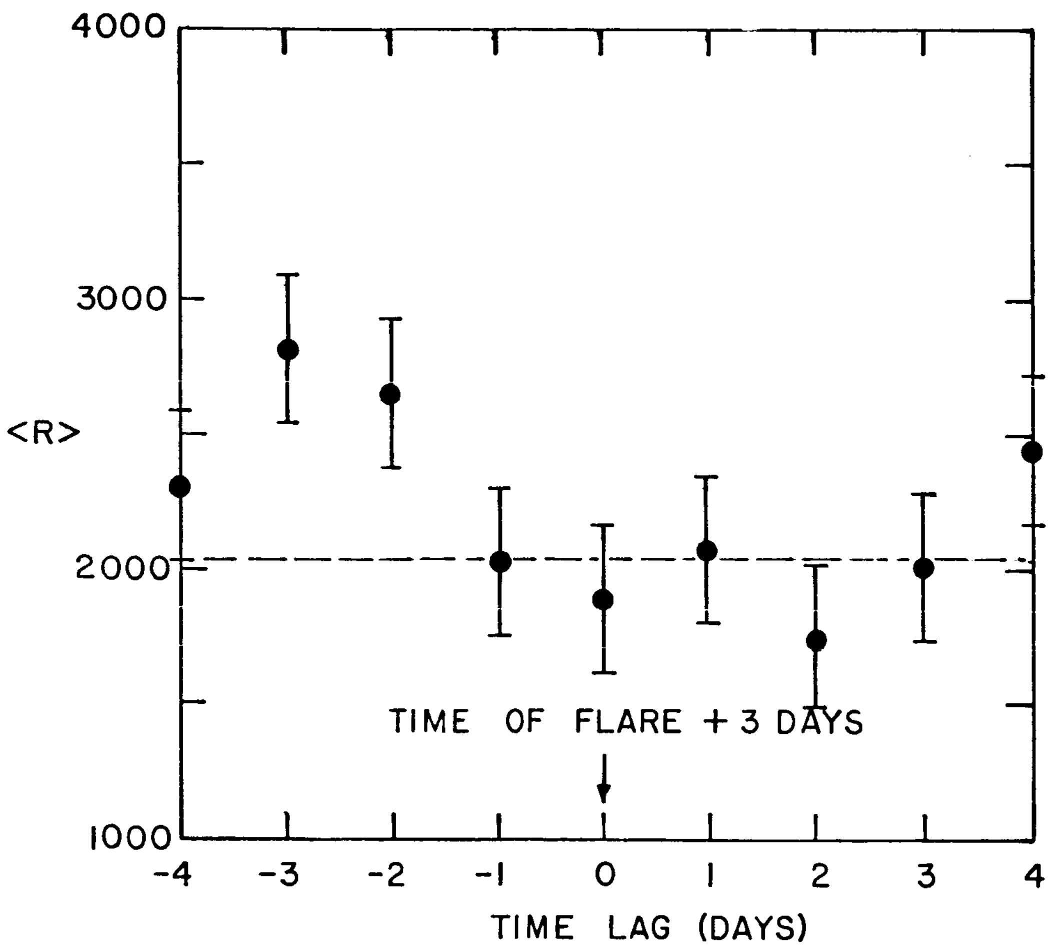

Figure 3. The average value of the $^4He^{++}/^3He^{++}$ flux ratio, <R>, over the duration of 7 separate $^3He^{++}$-enriched solar flare events as a function of the time delay between the observation of the flare and the measurement of solar wind $^3He^{++}$ and $^4He^{++}$. The horizontal scale has been chosen so that zero time delay corresponds to the solar wind transit time of three days. There is a horizontal dashed line at the position of the average of the nine values of <R>.

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Acknowledgements

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