

Solar Energetic Helium in March and June 1991

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Abstract

Helium nuclei in the energy range 50-110 MeV/nucleon from the ONR-604 experiment aboard the Combined Release and Radiation Effects Satellite (CRRES) are analyzed for the solar energetic particle events of 1991 March 22-28 and June 1-19. Spectra and helium isotopic ratios are examined and related to the morphological characteristics of gradual and impulsive SEP acceleration in an effort to identify the mechanism accelerating these helium particles. Short term enrichments of ^3He are observed in March that are consistent with impulsive acceleration. The $^3\text{He}/^4\text{He}$ ratio throughout March and June varies from 20 to over 400 times the solar wind value of ~ 0.0005 . Comparison is made to other related observations of solar energetic particle phenomena.

1 Introduction

Helium measurements from the ONR-604 experiment for nine large solar energetic particle (SEP) events in March and June 1991 have been previously presented (Chen et al., 1995; Guzik et al., 1995). The helium isotopic ratios and spectral characteristics were examined with the intent of identifying, if possible, the seed population for these large SEP events and the acceleration mechanism. In the present work, the temporal behavior of the helium spectra and $^3\text{He}/^4\text{He}$ ratios are presented, and the events are examined for characteristics of gradual, interplanetary shock-driven acceleration and impulsive acceleration in the solar flare itself. Related physical phenomena identified as diagnostic signatures of acceleration are tabulated for comparison with the helium data. The implications of the $^3\text{He}/^4\text{He}$ ratios are discussed.

2 Measurements

The nine large SEP events discussed in this work are listed in Guzik et al. (1995), except for June F, which is listed in Clayton et al. (1999). In Guzik et al. (1995) the time development of the particle flux amplitudes, spectral indices, and $^3\text{He}/^4\text{He}$ ratios was reported. These revealed a strong contrast between the time behavior of the $^3\text{He}/^4\text{He}$ ratio in March versus June. During March, the $^3\text{He}/^4\text{He}$ ratio averages 6-7%, but during events March A and March C two large, short-lived spikes in the $^3\text{He}/^4\text{He}$ ratio occur over timescales of 1-2 CRRES orbits (roughly 10 hours per orbit). This is in contrast to the stability of the $^3\text{He}/^4\text{He}$ ratio in June, during which the ratio hovers near 1% throughout the period and through the course of six separate SEP events. The mean value of the $^3\text{He}/^4\text{He}$ ratio in the solar wind is approximately 0.0005, a factor of about 20 less than the nominal value throughout June and as much as 400 times smaller than the peak values attained in March.

The time evolution of the helium spectral amplitude and power-law index for March A-C and June A-E was reported in Guzik et al. (1995). To check the agreement of the spectral measurements with a power law fit, Figure 1 plots the single-orbit average values of the spectral amplitude versus the spectral index. The data in Figure 1 are averaged over the portion of one orbit with $L > 6$, approximately four hours. No correlation is found, indicating that amplitude and index are independent parameters and a power law fit of

TABLE 1. Helium Spectral Indices, Isotopic Ratios, and Related Observations

| Event | Peak Spectral Index | Avg Spectral Index | $^3\text{He}/^4\text{He}$ ratio | | Radio Bursts (type) | SSC? | Gamma Rays?* |
|---------|---------------------|--------------------|---------------------------------|-------|---------------------|------|--------------|
| | | | Avg | Peak | | | |
| March A | 5.81±0.13 | 6.30±0.12 | 0.080 | 0.16 | II | Y | Y |
| March B | 7.23±0.32 | 7.49±0.29 | 0.045 | 0.06 | — | — | — |
| March C | 4.99±0.10 | 5.07±0.10 | 0.074 | 0.22 | III | — | — |
| June A | 3.05±0.38 | 3.33±0.30 | 0.012 | 0.017 | II,IV | Y | Y |
| June B | 4.00±0.18 | 4.19±0.29 | 0.010 | 0.011 | IV | — | Y |
| June C | 4.21±0.11 | 4.23±0.09 | 0.010 | 0.014 | IV | — | — |
| June D | 4.60±0.18 | 4.54±0.13 | 0.008 | 0.011 | II,IV | Y | — |
| June E | 4.11±0.19 | 4.31±0.17 | 0.013 | 0.024 | II,IV | — | — |
| June F | 4.32±0.14 | 4.28±0.16 | 0.012 | 0.014 | II,IV | Y | — |

* Absence of a verified observation does not preclude the occurrence of an event.

these two parameters is valid. Table 1 lists the helium peak and average spectral indices, and indicates that (1) to within error estimates, all SEP events except March A have the same indices for peak and average spectra; and (2) events June B, C, D, E, and F, assigned to the same NOAA region, have similar peak and average spectral indices, despite significant differences in their associated flare locations. The event-averaged spectral index varies somewhat during March, despite the three March events originating from within a relatively narrow heliolongitude band near the central meridian; whereas the spectral index is quite stable throughout June, while the June events track across nearly 180 degrees of heliolongitude (Clayton et al., 1999).

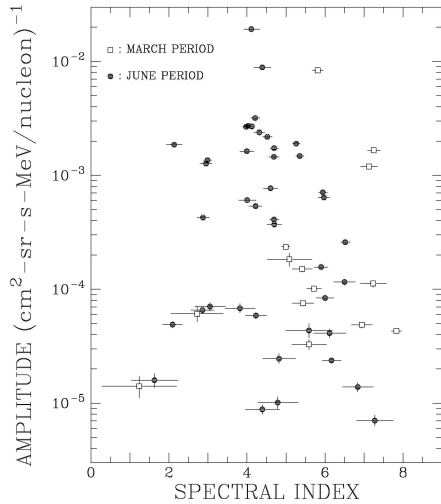


Figure 1. Helium spectral index vs. amplitude. Circles represent June and squares represent March.

coronal mass ejections and the accompanying shocks, while Type III bursts are identified with impulsive events. Sudden storm commencements indicate the arrival at the Earth of a strong interplanetary shock

Figure 2 shows the $^3\text{He}/^4\text{He}$ ratios versus spectral amplitude, and Figure 3 plots the ratios versus spectral index. Symbols and averaging times for Figures 2 and 3 are identical to Figure 1. The cross hatched area in both Figure 2 and Figure 3 is the region unavailable to the ONR-604 instrument. These figures show no correlation between the $^3\text{He}/^4\text{He}$ ratio and the helium spectral parameters. The independence of the $^3\text{He}/^4\text{He}$ ratio and the spectral index implies that shock acceleration does not change the $^3\text{He}/^4\text{He}$ ratio, and that the contributions to the ratio from diffusion and propagation are negligible.

The effort to identify large SEP events as being either gradual or impulsive in nature often includes a search for other distinct physical phenomena occurring in temporal coincidence with the SEP event, phenomena which are identified with varying degrees of certainty with either impulsive or gradual SEP acceleration (e.g., Bai, 1986). Table 1 lists the $^3\text{He}/^4\text{He}$ average and peak ratios alongside a tabulation of the coinciding occurrences of Type II, III, and IV radio bursts; geomagnetic sudden storm commencements (SSC); and gamma ray events from the sun. Type II and Type IV radio bursts are frequently associated with

(Hudson et al., 1997) and are consistent with a model of CME-driven shock acceleration of SEP particles. Gamma rays from the sun during a solar flare are produced by collision of the accelerated particles with solar material (Murphy et al., 1991) and are consistent with impulsive acceleration at the flare site.

3 Discussion

The measurements reported here contain elements suggestive of both impulsive and gradual SEP acceleration. However, the level of ^3He present throughout both time periods does not indicate the solar wind as the seed population for these events. During March, the $^3\text{He}/^4\text{He}$ ratio averages roughly 6-7%, but excluding the two large spike enrichments, the ratio lingers mostly around 3-5%. During March A and March C the ratio climbs abruptly to levels of 16% and 22%, over timescales of 10 and 20 hours, respectively. The timescale over which the ^3He enrichment occurs is consistent with an impulsive event. However, the level of $^3\text{He}/^4\text{He}$ before and after the impulsive spikes is itself 50-100 times greater than the mean solar wind value. During June, no impulsive-type short-term enrichments like those in March are seen. Instead the $^3\text{He}/^4\text{He}$ ratio holds steady near 1%, about 20% higher than in the solar wind.

Only for March C were enough ^3He events available to calculate a separate ^3He spectrum (Chen et al.,

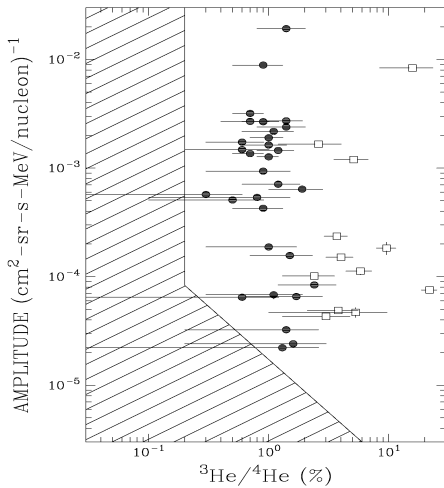


Figure 2. $^3\text{He}/^4\text{He}$ ratio vs. helium spectral amplitude. Symbols same as Figure 1.

energy. At low energies, the ^3He in March C does not seem to be suppressed relative to the solar wind; rather, ^3He is enriched relative to the solar wind at high energies.

The stability of the spectral indices in June, as events are seen across a broad band of heliolongitudes, is consistent with gradual acceleration by interplanetary shocks, as the shocks are able to cross field lines so the particles they accelerate need not originate from well-connected sites at the sun. This does not necessarily indicate that the seed population is the solar wind, however, since the $^3\text{He}/^4\text{He}$ ratios remain considerably higher than the mean solar wind values throughout June. But CME-driven shock acceleration of material pre-enriched in ^3He in the corona or elsewhere is not excluded.

The morphological information tabulated in Table 1 supplements the CRRES helium measurements with separate observations indicative of both gradual and impulsive acceleration. However, certain events are correlated to a lesser or greater extent with one or the other type of SEP acceleration. March C exhibits diagnostic indications only of impulsive acceleration, with a Type III radio burst, a strong spike-like enrichment of ^3He , and no indicators of gradual acceleration. June C, D, E, and F, conversely, witness radio

1995). When the March C spectra for ^3He and ^4He are compared, it is found that the somewhat flatter spectrum of ^3He versus ^4He yields $^3\text{He}/^4\text{He}$ ratios that are an increasing function of energy. Extrapolating the measured spectra reported in Chen et al. (1995) down to ~ 1 MeV/n, comparable to the energy of the solar wind, the inferred $^3\text{He}/^4\text{He}$ ratio at 1 MeV/n for March C is in good agreement with the solar wind ratio. If the solar wind helium is taken to be the source population for this event, then some aspect of the acceleration or transport of the helium to the Earth must account for either an enrichment of ^3He or a suppression of ^4He to produce the observed spikes in the $^3\text{He}/^4\text{He}$ ratio. In March A, the spike in the $^3\text{He}/^4\text{He}$ ratio occurs in coincidence with the peak in the ^4He flux, which suggests that the increase in the $^3\text{He}/^4\text{He}$ ratio is due to an enrichment of ^3He rather than a suppression of ^4He . Furthermore, the fact that the extrapolated March C $^3\text{He}/^4\text{He}$ ratio at ~ 1 MeV/n agrees with the solar wind ratio while the ratio in the 50-110 MeV/n range is 1-2 orders of magnitude greater is not consistent with a stream-limiting effect in which the different A/Z of ^3He and ^4He leads to an apparent suppression of $^3\text{He}/^4\text{He}$ at low

bursts consistent with interplanetary shocks, SSC events for June D and F, and no clear diagnostics of impulsive acceleration; while the $^3\text{He}/^4\text{He}$ ratio remains stable throughout the June period. These June events are consistent with gradual acceleration, provided some mechanism or seed population is found to account for the $^3\text{He}/^4\text{He}$ ratio of $\sim 1\%$. Neither the events in June nor in March are consistent with the solar wind as the seed population.

For the remaining events, a combination of indicators of both gradual and impulsive acceleration is seen. March A sees a spike enrichment of ^3He , and gamma rays associated with the March A flare have also been inferred from CRRES measurements (Clayton et al., 1999). However, the radio bursts and occurrence of a

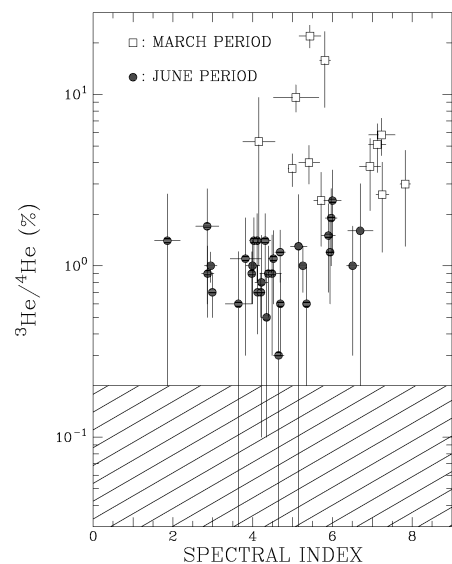


Figure 3. $^3\text{He}/^4\text{He}$ ratio vs. helium spectral index. Symbols same as Figure 1.

SSC at the Earth indicate the presence of a strong interplanetary shock in conjunction with March A. In June, events June A and B have corresponding radio burst measurements consistent with interplanetary shocks, and June A also witnesses a SSC event caused by a strong shock arriving at the Earth. Yet both June A (Ramaty et al., 1997) and June B (Murphy et al., 1997) are accompanied by solar gamma ray events consistent with some, possibly additional, particle acceleration at the sun.

4 Summary

The CRRES observations of helium from nine large SEP events in March and June 1991 indicate that the seed population for these events is not solar wind helium. Mean levels of the $^3\text{He}/^4\text{He}$ ratio are consistently one or more order of magnitude greater than the mean ratio in the solar wind. Large enrichments of the $^3\text{He}/^4\text{He}$ ratio above the mean level in March are consistent in their duration and magnitude with impulsive solar flare acceleration. In June, the stability of the helium spectral characteristics witnessed across a broad band of heliolongitudes is consistent with gradual interplanetary shock acceleration. However, certain SEP events in both March and June are accompanied by separate physical measurements, i.e., radio

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