HIGH-ENERGY ^{3}He-RICH SOLAR PARTICLE EVENTS

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Abstract. Energetic particle observations of the ERNE instrument on board SOHO enable measurements of ^{3}He and ^{4}He fluxes beyond 15 MeV nucleon^{-1} with good statistical resolution. We report results of a survey of the ERNE observations covering the period from 8 February 1999 to 6 December 2000. We find 10 and 5 days during which the ^{3}He-to-^{4}He ratio exceeds the levels of 20% and 50%, respectively. Those periods include, in particular, four ^{3}He-rich events that are sufficiently strong for a reasonably accurate estimate of the time-intensity profiles. We analyze the history of solar and interplanetary phenomena associated with these high-energy ^{3}He-rich events. Basic properties of such events and significant solar and interplanetary factors are formulated. The significant factors comprise, in particular, a strong, impulsive flare, typically observed about $\frac{2}{3}$ day before the ^{3}He onset, and an interplanetary shock wave or magnetic field enhancement arriving at 1 AU about $\frac{4}{3}$ day after the ^{3}He onset. The high-energy ^{3}He-rich events make up a new kind of hybrid events, possessing the impulsive-type composition and the gradual-type time-profiles. We emphasize a dependence of the resultant particle event on the history of the particular solar eruption comprising coronal mass ejection (CME) and the flare associated with the CME.

1. Introduction

A typical ^{3}He-rich event may be defined as a weak solar energetic particle (SEP) event that is strongly enhanced in the isotope ^{3}He, $^3\mathrm{He}/^4\mathrm{He} \gtrsim 0.1$, in association with an impulsive solar flare in the western hemisphere of the Sun (see reviews by Kocharov and Kocharov, 1984; Reames, Meyer, and von Rosevinge, 1994). These events are observed in the low-energy range 0.1–10 MeV nucleon^{-1} because of a strong decline of the ^{3}He intensity with increasing energy. It is widely accepted that the ^{3}He-rich composition is produced in flares, whereas a 'normal' composition with $^3\mathrm{He}/^4\mathrm{He} \approx 5 \times 10^{-4}$ was expected from interplanetary shocks (Reames, 1995; Roth and Temerin, 1997; Miller *et al.*, 1997; Litvinenko, 2000; Zank, Rice, and Wu, 2000). However, recent ACE observations revealed a number of low-energy ^{3}He enhancements associated with interplanetary CME shocks (Desai *et al.*, 2001). The ACE observations are done in the traditional, for ^{3}He-measurements, energy range of 0.5–2.0 MeV nucleon^{-1}, and late in time when the shock is already close to 1 AU. In all reported events but one, the ^{3}He/^{4}He ratio was below 0.2, typically

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≈ 0.04. Mason, Mazur, and Dwyer (1999) suggested that a long-living 'reservoir' of supra-thermal ions available at 1 AU, with ^{3}He/^{4}He $\approx 0.01 - 0.02$, may provide a seed population for further acceleration at interplanetary shocks. Such a 'reservoir' might be filled with the remnant material from previous impulsive SEP events.

A few measurements of ^{3}He beyond 10 MeV nucleon^{-1} are available (Hsieh and Simpson, 1970; Dietrich, 1973; Anglin, 1975; Chen, Guzik, and Wefel, 1995; Clayton, Guzik, and Wefel, 2000). In the previous solar maximum, the ^{3}He/^{4}He ratios for SEPs over the high-energy range were determined by Chen, Guzik, and Wefel (1995). In particular, for a period around $\sim$ 02 UT on 24 March 1991, the ^{3}He/^{4}He ratio at 43–94 MeV nucleon^{-1} was estimated as $0.16 \pm 0.08^*$ (Clayton, Guzik, and Wefel, 2000). That event was associated with a strong, impulsive solar flare of 22 March 1991 (X9.4/3B, S26°E28°), chromospheric Moreton wave, and two interplanetary quasi-perpendicular shocks near the Earth (Krupp *et al.*, 1992; Naidu *et al.*, 1992; Blake *et al.*, 1992; Ermakov *et al.*, 1993; Kocharov *et al.*, 1995). Clayton, Guzik, and Wefel (2000) pointed out that the 24 March 1991 ^{3}He-peak is attained in the SEP event associated with interplanetary shock. Recently Torsti *et al.* (2002) reported on the SEP event of 29 October 2000 with exceptionally high ^{3}He intensity and high ^{3}He/^{4}He ratio, > 100%, observed in the high-energy energy range, up to 70 MeV nucleon^{-1}. However, basic properties of high-energy ^{3}He-rich events have not yet been formulated.

Here we present results of a systematic inspection of SOHO/ERNE data on ^{3}He enhancements in the energy range >15 MeV nucleon^{-1}. In Section 2, we describe the observed ^{3}He-rich events in terms of particle fluxes and associated solar and interplanetary phenomena. Then we will formulate and discuss solar and interplanetary factors dominating appearance of the ^{3}He-rich composition in the high-energy range (Section 3). A summary of our result is given in Section 4.

2. Observations

We report on the ^{3}He-flux enhancements observed by the High-Energy Detector (HED) of the Energetic and Relativistic Nucleon and Electron experiment (ERNE) on board the Solar and Heliospheric Observatory (SOHO) spacecraft (Torsti *et al.*, 1995). The data comprise the ^{3}He and ^{4}He flux measurements in the energy range 15–30 MeV nucleon^{-1} for the period 8 February 1999–6 December 2000. We also present a number of relevant solar images obtained with the Extreme-UV Imaging Telescope (EIT) on board SOHO (Delaboudinière *et al.*, 1995). The EIT difference images shown in this paper have been corrected for the solar rotation (re-rotated). The Large Angle and Spectrometric Coronagraph Experiment (LASCO) results are used to identify associated coronal mass ejections (Brueckner *et al.*, 1995). We start

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[*] Hereinafter, we will measure the abundance ratio in percent, so that for the 24 March 1991 event it will be ^{3}He/^{4}He $= 16 \pm 8\%$. The 100% will mean ^{3}He/^{4}He $= 1$.

TABLE I

^{3}He-event days with ^{3}He/^{4}He > 20% at 15–30 MeV nucleon^{-1}.

Event number	Day	^{3}He counts[a]	^{3}He intensity (m^2 s sr MeV nucleon^{-1})$^{-1}$	^{3}He/^{4}He %	σ %
1	31 May 1999	14	0.0036	25	14
2	18 June 1999	97	0.0242	22	3
3	2 July 1999	16	0.0041	32	16
4	14 Aug. 1999	104	0.0260	24	3
5	23 Dec. 1999	25	0.0062	141	116
	24 Dec. 1999	165	0.0412	147	25
	25 Dec. 1999	72	0.0180	252	128
6	14 Oct. 2000	16	0.0041	24	8
7	29 Oct. 2000	274	0.0687	170	19
	30 Oct. 2000	1954	0.490	102	3

[a] Exceeding the background counts.

this section with formulation of selection criteria for a ‘well observed’ high-energy ^{3}He-rich event, and then perform a case study of each event selected.

2.1. EVENT SELECTION

At the first step of selection, we adopt $^3\text{He}/^4\text{He} = 20\%$ as a threshold for the high-energy ^{3}He rich period to be analyzed. Table I summarizes all 10 days exceeding this criterion. Five of the enhancements reveal high ^{3}He count rate for no more than one day. The events 5 and 7 have high ^{3}He count rate over periods of 3 and 2 days, respectively. Both have ^{3}He/^{4}He ratios above 100%.

For selection of a particular ^{3}He event for the detailed analysis we use, besides the ^{3}He/^{4}He ratio, a count statistics criterion. We require that the count rate of the whole ^{3}He event in the energy range 15–30 MeV nucleon^{-1} is $\gtrsim$100, which allows time-intensity and abundance-ratio profile estimations with reasonable accuracy. This selects events 2, 4, 5, and 7 for further analysis. The intensity profiles and development of the helium-isotope ratio during the events is shown in Figure 1. Special features of ^{3}He flux of the selected events are given in Table II. A collection of properties of coronal mass ejections (CMEs) associated with selected ^{3}He-rich events is given in Table III.

2.2. EVENT OF 18 JUNE 1999

Figure 1(a) shows that the ^{3}He event first appears above the background fluctuations at about 10 UT on 18 June 1999. However, the excess over the averaged background level is weak until about 18 UT when a rapid intensity rise brings the

TABLE II

Characteristics of the most intensive ^{3}He-rich events in the energy range 15–30 MeV nucleon^{-1}.

Onset of ^{3}He event		Onset-to-max.	Duration	Maximum intensity	^{3}He/^{4}He
Date and time (±1 hr)	Delay (after dominant X-ray flare[a])	time (hr)	(hr)	(m^{2} s sr MeV nucleon^{-1})$^{-1}$	%
18 June 1999 10:00 UT	17 hr (M3.6, ∼W100°[b], 17 June 17:30 UT)	10 ± 2	27 ± 3	0.22	22 ± 3[c]
14 Aug. 1999 04:00 UT	13 hr (C5.3, W25°[b], 13 Aug. 15:15 UT)	4 ± 1	34 ± 3	0.075	24 ± 3[d]
23 Dec. 1999 15:00 UT	20 hr (M5.3, E19°, 22 Dec. 19:04 UT)	16 ± 2	58 ± 5	0.085	164 ± 18[e]
29 Oct. 2000 18:00 UT	16 hr (M4.4, E35°, 29 Oct. 01:57 UT)	19 ± 2	98 ± 5	1.6	240 ± 15[f]

[a] The X-ray class, longitude, date and peak time of the most powerful flare during one day preceding the onset of a ^{3}He-rich event are shown in brackets.

[b] EIT observations. Corresponding Hα flare is not reported in *Solar Geophysical Data (SGD)* 1999b.

[c] During first 14 hours of the event.

[d] During first 20 hours of the event.

[e] During first 40 hours of the event.

[f] During first 6 hours of the event.

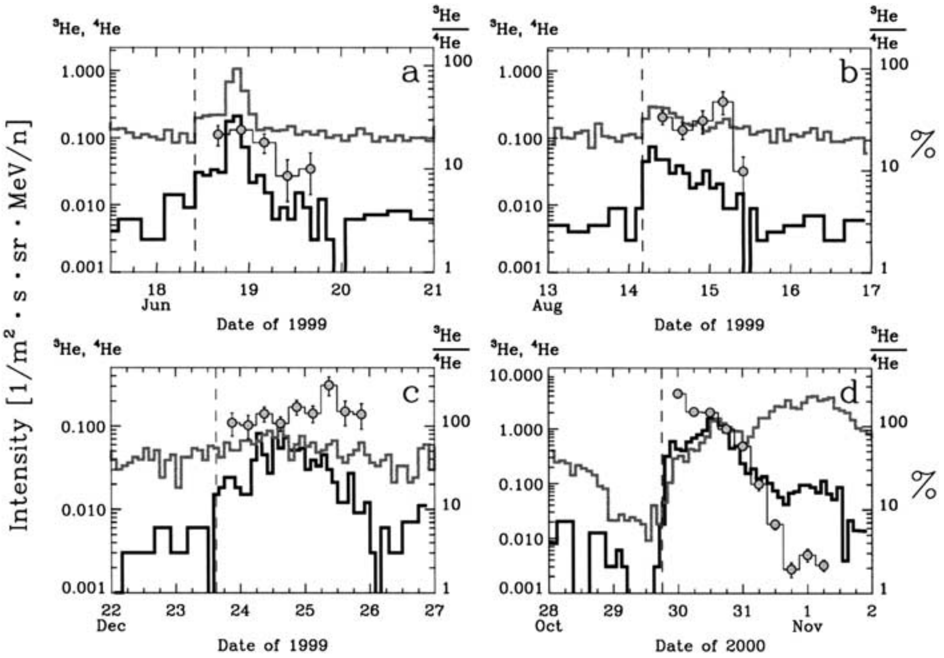

Figure 1. Time–intensity profiles of the ^{3}He and ^{4}He fluxes (respectively *black* and *gray lines*) and the background-free ^{3}He/^{4}He ratio (points) during the selected events in the energy range 15–30 MeV nucleon^{-1}. (a)–(d) show the 18 June, 14 August, 23 December 1999, and 29 October 2000 events, respectively. Onset times of ^{3}He-rich events are indicated with *vertical dashed lines*.

^{3}He intensity into a 6-fold higher level, to about 0.22 ^{3}He/(m^2 s sr MeV nucleon^{-1}). The fast rise of ^{3}He is correlated with the onset of the rapid main rise of proton and ^{4}He intensities at 18:20 UT ± 10 min and 18:45 UT ± 10 min, respectively. The preliminary enhancement in proton and ^{4}He intensity started at ~ 10 UT. The ^{3}He/^{4}He ratio averaged over the first 14 hours of the event is 22±3% in the selected channel 15–30 MeV nucleon^{-1}.

Inspection of GOES soft X-ray data for a day preceding the ^{3}He onset reveals an impulsive flare of class M3.6 (17:30 UT, 17 June 1999) and few minor bursts of class C (*SGD*, 1999a). No optical flare is reported for the M3.6 burst. However, the SOHO/EIT images at 195 Å show that the M3.6 X-ray flare is caused by the northern-western (NW) limb activity. A large flare occurred between the images at 17:22 and 17:29 UT, and loops were seen expanding away from the NW limb. The EIT difference image (Figure 2(a)) displays also clear over-the-limb dimmings (i.e., a transient coronal hole) indicative of presence of an associated CME (e.g., Hudson and Cliver, 2001). However, the interplanetary magnetic field (IMF) data from Wind/MFI (Lepping *et al.*, 1995) and solar wind profiles from the CELIAS Proton Monitor on SOHO (Hovestadt *et al.*, 1995) show no distortions arriving at the near-Earth spacecraft (Figure 3(a)). These observations suggest that the NW limb CME moved sideways of the Earth. Note also a concurrent, slow loop CME from behind the northern-eastern (NE) limb seen in EIT images from 17:01 to 18:24 UT, 17 June 1999. Unfortunately, LASCO data for the 17–18 June period are missing.

An evolution and possible second eruption from the same NW active region was observed by EIT during 11:14–11:56 UT on 18 June 1999. The next, third NW eruption was observed at 16:19–17:56 UT. It was narrow but fast, again including dimmings (Figure 2(b)), and later expanded into an additional outflow of a trans-equatorial loop, spanning from the NW active region to one in the SW. There was also an eruption in the NE during 16:39–17:21 UT. These eruptions were associated with a gradual class C5.8 X-ray flare with maximum at 16:57 UT. The flare fits well with the main rise of ^{3}He flux observed at 18:00 UT ± 1 hour on 18 June 1999 (Figure 3(a)). The fourth, 'fountain-like' CME from the same NW region was observed by EIT at 21:36–22:46 UT on 18 June 1999.

Both M3.6 and C5.8 flares were accompanied by metric radio bursts of type III, type V, and type II (*SGD*, 1999a). Also a possible type IV radio burst was registered in association with the C5.8 flare. No interplanetary type II bursts is seen in the WIND/WAVES frequency range below 13.8 MHz (Bougeret *et al.*, 1995). The interplanetary magnetic field (WIND/MFI) and solar wind (SOHO/CELIAS) profiles for 18 June 1999 are very smooth. Therefore it seems unlikely that the observed structure of particle profiles is of a local origin. The solar wind speed stayed close to 400 km s^{-1}.

Note that the 16.5-hour delay between the dominant M3.6 flare and the ^{3}He onset might make the association questionable, if similar patterns were not observed also in all other events (see below and Table II). Besides, the M3.6 flare and corresponding NW CME made up the latest significant eruption preceding the ^{3}He-rich event of 18 June 1999.

2.3. EVENT OF 14 AUGUST 1999

On 14 August 1999, the onsets of proton, ^{3}He, and ^{4}He fluxes at the SOHO location are observed at 04:00 UT ± 40 min (Figure 1(b)). In contrast to other events, the rise of the 14 August 1999 event is fast, so that maximum intensity is reached in 3–5 hours from the onset (Table II). The maximum is followed by a smooth, nearly exponential intensity decay. The duration of the decay phase is 1.5 days. No significant variation is observed in the ^{3}He/^{4}He ratio, excluding perhaps the last time bin in Figure 1(b). An average value of the ratio is 24 ± 3%.

There were a number of X-ray bursts and CMEs recorded during 13 and 14 August 1999 (Figure 3(b) and Table III). According to the EIT 195 Å observations, the most important general feature of the entire time interval was a predominant and almost continuous activity in the SW quadrant in AR 8662 (around S15° W30°). This activity was combined with noticeable activity in AR 8668 (N21° E73°) (Figure 2(c)). Also many type III radio bursts were registered during 13–14 August 1999, but no type II (*SGD*, 1999b).

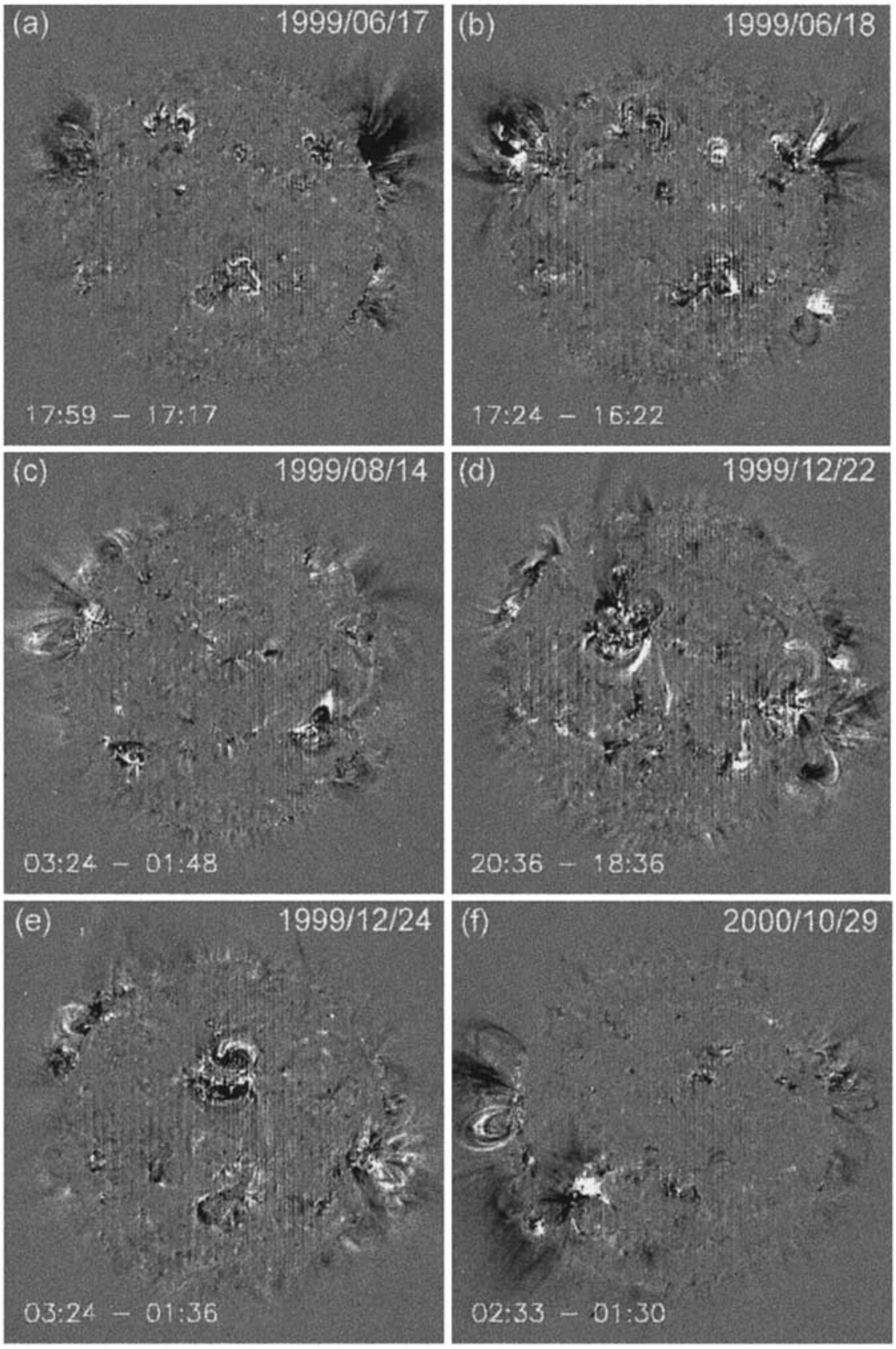

Figure 2. The SOHO/EIT 195 Å re-rotated difference images relative to the corresponding pre-flare heliograms illustrating flare activities associated with the 18 June 1999 (a, b), 14 August 1999 (c), 23 December 1999 (d, e), and 29 October 2000 (f) particle events. Some additional comments and detailed illustrations (including various images and movies) of the solar activity related to all four events can be found at the web site *http://helios.izmiran.troitsk.ru/lars/Chertok/Helium/index.html*.

TABLE III

High-energy ^{3}He-rich events and accompanying coronal mass ejections[a].

^{3}He-rich events		Coronal mass ejections
Onset date and time (UT ±1 hr)		Instrument[b]: CME signature (date and first appearance time, UT)
18 June 1999	10:00	EIT: NE CME (17 June 1999 17:01)
		EIT: eruption over NW limb (17 June 1999 17:29)[c,d]
		LASCO: no data
14 Aug. 1999	04:00	LASCO: W CME (13 Aug. 1999 04:30)
		LASCO: partial halo CME (13 Aug. 1999 15:54)[c]
		LASCO: halo CME (13 Aug. 1999 21:54)
		LASCO: W CME 406 km s^{-1} (14 Aug. 1999 02:30)[d]
		CELIAS: *in situ* shock (15 Aug. 1999 09:52)
23 Dec. 1999	15:00	LASCO: halo CME 570 km s^{-1} (22 Dec. 1999 02:30)
		LASCO: N CME (23 Dec. 1999 11:30)
		LASCO: halo CME 605 km s^{-1} (22 Dec. 1999 19:31)[c]
		LASCO: N CME 620 km s^{-1} (23 Dec. 1999 06:30)
		LASCO: N CME 64 km s^{-1} (23 Dec. 1999 07:54)
		LASCO: S CME 412 km s^{-1} (23 Dec. 1999 08:54)[d]
29 Oct. 2000	18:00	EIT: NW filament, CME (29 Oct. 1999 00:48)
		EIT: SE CME (29 Oct. 2000 00:55)[c]
		WAVES: type II shock 660 km s^{-1} (29 Oct. 2000 02:05)[c]
		EIT: possible NE CME (29 Oct. 2000 09:04)
		EIT: NW CME (29 Oct. 2000 15:58)[d]
		LASCO: no data
		CELIAS: *in situ* shock (31 Oct. 2000 16:22)

[a] Lists all significant eruptions observed before the ^{3}He onset time and also the interplanetary shocks as they arrived at 1 AU.

[b] For periods of LASCO observations the EIT data are not listed in the table but discussed in text.

[c] Eruption associated with a dominant X-ray flare (see Table II).

[d] The latest eruption preceding the onset of ^{3}He-rich event.

In contrast to other high-energy ^{3}He-rich events, there were no M class flares within at least one day prior to the event. The strongest X-ray flare was of class C5.3, peaked at 15:15 UT on 13 August 1999 (Table II). No corresponding Hα flare is reported in (*SGD*, 1999b). However, a flare from AR 8662 on the SW disk was observed at 15:23 UT by EIT. A LASCO partial halo CME appeared at 15:54 UT, starting in the NE with a later front in the west. The cross-disk activities in the NE and SW regions, and the CME starting in the NE and continuing in the west, indicate that the eruption may be centered to the NE of the C5.3 flare in AR 8662. Note also the second, almost identical-looking halo CME that was observed by LASCO at 21:54 UT (Table III). Before the second LASCO CME, at 19:13–20:12 UT, EIT observed a CME, dimming from the SW AR 8662.

During 01:48–03:24 UT on 14 August 1999, EIT observed a small faint CME/dimming from the NW limb, expanding to a trans-equatorial loop CME at the west limb, which corresponds well with the 02:30 UT CME observed by LASCO (Table III), the source is apparently behind the limb. No apparent EIT wave is observed from there, but evolution is seen in an active region in the SW on the disk (Figure 2(c)). This eruption shortly preceded the onset of the particle event at SOHO.

During the particle event, the solar wind speed was very low, about 330 km s^{-1}, until 09:52 UT on 15 August 1999 when an interplanetary shock wave was observed *in situ* by the CELIAS Proton Monitor on board SOHO. Arrival of the shock is also seen in the magnetic field intensity profile recorded on board WIND (WIND/MFI data, shown in Figure 3(b)). This shock might be launched by one of the eruptions observed during 13 August 1999. Based on Table III, we estimate that if the shock was launched at 04:30 UT or 15:54 UT the transit speed of the shock was about 780 km s^{-1} or 990 km s^{-1}, respectively.

2.4. EVENT OF 23 DECEMBER 1999

The time profile of the high-energy ^{3}He-rich event consists of a minor enhancement of ^{3}He flux starting at 15 UT ± 1 hour on 23 December and a main rise at 05:00 UT ± 1 hour on 24 December 1999 (Figure 1(c)). Only weak enhancement of the ^{4}He flux and no enhancement in the proton channel is seen at the first ^{3}He-rise time, probably because they are masked by a previous enhancement started about 24 hours earlier. The background-free ^{3}He/^{4}He ratio averaged over the first 40 hours is $164 \pm 18\%$. As shown in Figure 1(c), the ratio was quite stable or slightly increasing during the event.

The dominant X-ray burst M5.3 (19:04 UT, 22 December 1999) was located at N24° E19° in AR 8806/8807 (*SGD*, 1999c; Figure 2(d)). Note a preceding flare in the same active region, X-ray class M1.8 at 02:16 UT. The temporal separation of ^{3}He onset from the M5.3 flare is large, 20 hours, but remarkably similar to the delay observed on 18 June 1999 (Table II). The activity in AR 8806/8807 was combined with a noticeable activity in the south-western region AR 8803/8798 (S15° W40°) and nearby. The WIND/WAVES experiment registered a hectometric type III burst corresponding to the M5.3 flare. A metric type I storm proceeded through 22:45 UT of the same day (*SGD*, 1999c). In association with the M5.3 flare and radio bursts, a halo CME appeared in the LASCO field of view first at 19:31 UT 22 December 1999 (Table III). The 19:31 UT CME, as well as the 02:30 UT CME associated with the M1.8 flare, had the strongest brightening to the north.

The EIT observed a number of eruptions from the northern AR 8806/8807. At 01:34 UT on 22 December 1999, an eruption started from this active region

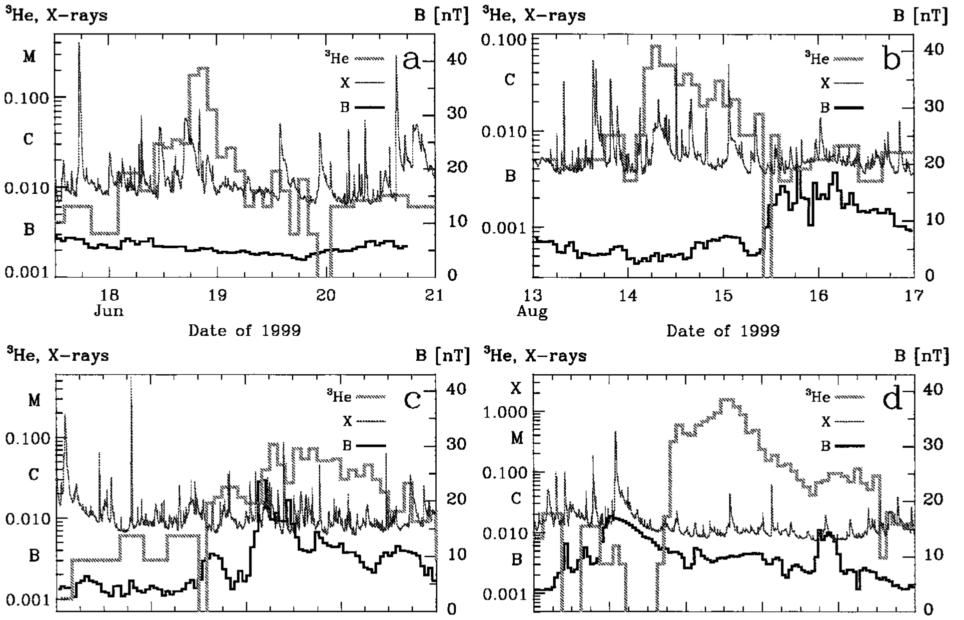

Figure 3. Time–intensity profiles of the soft X-rays (1–8 Å), the 15–30 MeV nucleon^{-1} ^{3}He nuclei, and the interplanetary magnetic field *B*, for the particle events of 18 June 1999 (a), 14 August 1999 (b), 23 December 1999 (c), and 29 October 2000 (d). Intensity of ^{3}He (*gray histogram*) is shown on a left, logarithmic axis, with numbers in units 1/(m^2 s sr MeV nucleon^{-1}). Intensity of the X-ray emission (*fine curve*) is shown on the same, left axis in units watts hm^{-2} and also with letters (e.g., C labels a decade starting at 0.01 Watts hm^{-2}). A right, linear axis is for the interplanetary magnetic field strength (*black, lower histogram*) measured in nT (WIND/MFI data).

in the NE and continued with an EIT wave disturbance propagating to the NW. Bright flare, eruption and some dimming were observed during 19:11–19:58 UT on 22 December 1999, in association with the above-mentioned dominant X-ray flare of class M5.3. During 04:11–07:11 UT on 23 December, there was additional flaring and 'bubbling' from the same, NE active region, followed at 07:34 UT by eruption and outflow from the SW AR 8803/8798. The NE AR 8806/8807 had also continuous 'spurts' coming from it, particularly from the northern part of it. Clear spurts were seen on the 23rd at 08:34, 10:10, 19:34 UT, and on the 24th at 00:10, 02:10, 04:22, 04:58, and a large one at 05:35 UT. Along with the latter activities in the AR 8806/8807, a few eruptions can also be distinguished from the SW AR 8803/8798 (Figure 2(e)).

The EIT eruptions and the LASCO CMEs (Table III) that were observed during 4–10 UT on 23 December preceded the onset of the particle event by 5–11 hr, whereas the EIT spurts in the beginning of 24 December fit with the main rise of the ^{3}He flux registered at 05:00 UT ± 1 hr on 24 December 1999. However, the corresponding X-ray bursts were relatively weak (Figure 3(c)). There were also many metric type III bursts before the onset and close to the main rise of the particle event, respectively at 00–13 UT on 23 December and at 02–05 UT on 24 December 1999 (*SGD*, 1999c).

With two halo CMEs observed by LASCO on 22 December (Table III), the CELIAS solar wind profiles did not reveal a well-developed shock wave arriving at SOHO. However a strong enhancement (compression) in the interplanetary magnetic field intensity, above 20 nT, was still recorded by WIND/MFI arriving at 1 AU in the beginning of 24 December 1999 (Figure 3(c)). It is seen from the figure that the main rise of ^{3}He intensity in this event might be affected or even entirely produced by this magnetic compression, whose arrival at 1 AU coincided by chance also with the above-listed phenomena on the Sun. By assuming that the magnetic compression was launched at 02:30 UT or 19:31 UT on 22 December 1999 (Table III), we estimate the transit speed to be about 900 km s^{-1} or 1410 km s^{-1}, respectively, whereas the LASCO CME speeds in both cases were of order of 600 km s^{-1}. The latter supports the transit speed of 900 km s^{-1} rather than 1410 km s^{-1}, and correspondingly the association with the 02:30 UT LASCO CME seems more likely.

2.5. EVENT OF 29 OCTOBER 2000

The 29 October 2000 event is the strongest high-energy ^{3}He-rich event ever observed, an order of magnitude more intense than any other event in Table I. We estimate that the onset of ^{3}He flux on 29 October 2000 is at 18:00 UT ± 1 hour. The first rise is fast, but the intensity maximum, 1.6 ^{3}He/(m^2 s sr MeV/nucleon^{-1}), is registered about 19 hr later (Figure 1(d)). In the energy range 15–30 MeV nucleon^{-1}, the proton flux shows a slight, 50% enhancement starting at 07:20 UT ± 20 min, and a stronger increase from 18:10 UT ± 10 min onwards. The flux of ^{4}He during 18–20 UT is weak, but starts rising strongly at about 20 UT. The ^{3}He decline phase is fast in the beginning, but becomes slower later. The shock passage, as observed by the CELIAS proton monitor on board SOHO at 16:22 UT on 31 October 2000, generates a bump in the particle intensity. The duration of the decline phase is 3 days, which means that the duration of the whole ^{3}He event is exceptionally long, $\approx$ 98 hours (Table II). The abundance ratio ^{3}He/^{4}He shows a strong temporal development. In the early rise phase, the ratio reaches 240%. During the intensity peak the ratio declines smoothly, then falls down to 1–2% level in the middle of the particle events, and keeps that lower level until the end of the event. There are clearly two phases in the event, before and after $\approx$ 02 UT on 31 October 2000. A transition of the spacecraft from one magnetic flux tube to another may be a reason for the two different periods observed (Torsti *et al.*, 2002).

The list of Hα and X-ray flares in *SGD* (2000) shows that a dominant flare is a class M4.4 X-ray flare located at S25° E35° (AR 9209), with maximum at 01:57 UT on 29 October 1999 (Table II). The EIT observed during 00:55–02:12 UT a dimming, CME, and EIT wave from the region of the flare. One can see from the EIT difference image (Figure 2(f)) that this event was accompanied by large-scale activity in the eastern hemisphere. There were also corresponding metric type III, type II, and type IV radio bursts (*SGD*, 2000). A fast evolution in the NE and possible CME were observed by EIT also during 09:04–09:32 UT, 29 October 1999.

No Hα flare took place in the western solar hemisphere on 29 October 2000. However, CME/filament eruptions were observed by EIT in the NW during 00:48 –02:26 UT, 15:58–17:55 (off-limb), and 19:14–21:32 UT. The WIND/WAVES receiver detected two hectometric type III bursts shortly before 02:00 UT in association with an M4.4 flare and then at around 16:30 UT, 29 October 2000. The latter seems to originate from beyond the western limb (Torsti *et al.*, 2002). The NW off-limb eruption observed by EIT and WAVES at around 16:30 UT fits well with the onset of the particle event. However, onset of this event might be affected by the magnetic cloud that passed the Earth not long before the ^{3}He rise (the cloud passage is seen in Figure 3(d) as a smooth enhancement of the magnetic field intensity with maximum around 00 UT 29 October 2000; WIND/MFI observation).

The LASCO observations are lacking, but as mentioned, the CELIAS Proton Monitor registered a shock passage at 16:22 UT on 31 October 2000. If the shock was launched at around the time of the dominant, M4.4 class flare, as the WAVES dynamic spectrum suggests, the shock transit speed was about 660 km s^{-1} (Torsti *et al.*, 2002). Arrival of the shock is seen also in the interplanetary magnetic field profile shown in Figure 3(d) (WIND/MFI data).

3. Discussion

3.1. OCCURRENCE OF HIGH-ENERGY ^{3}He-RICH EVENTS

Our survey shows that the frequency of ^{3}He-rich events in the high-energy range > 15 MeV nucleon^{-1} was low during 1999–2000 (Table I), even though the solar maximum was in progress. Only four events have ^{3}He/^{4}He ratio above 20% and are intense enough to resolve their time structure (Table II).

Overall time profiles are prolonged, but not identical. Profiles of the June, December 1999 and October 2000 events reveal very long onset-to-maximum times (Table II), which might be typical for gradual events, especially for gradual events launched by a solar eruption in the eastern hemisphere (e.g., Cane, Reames, and von Rosenvinge, 1991). The event on 29 October 2000 is an order of magnitude stronger than the three other events (Table II). Also the ^{3}He/^{4}He ratio is extremely high, of the order of 200% in the beginning of the event. Such a value would be among the highest values even for impulsive SEP events.

The high-energy ^{3}He-rich events are very rare and consequently are brought on by several solar/interplanetary factors acting in concert. We consider an accompanying factor to be significant if it is met in at least three ^{3}He-rich events among the four events analyzed. With the data now in hand, the significant factors for appearance of high-energy ^{3}He-rich events are the following:

(1) A dominant, typically M class, impulsive soft X-ray flare that occurs 13–20 hours before the onset of the particle event (Table II and Figure 3).

(2) An interplanetary shock wave and/or an enhancement (compression) in the interplanetary magnetic field intensity above 10 nT, arriving at 1 AU about two days after the dominant flare and about 1.3 day after the onset of the ^{3}He-rich event (Figure 3). Estimated transit speeds are from 660 km s^{-1} to 990 km s^{-1}.

(3) A large angular separation between the connected-to-detector interplanetary magnetic line and the dominant flare, from about 40° to 100° in the heliocentric angle (Table II).

(4) Additional solar eruptions (Table III).

It seems that the acceleration of ^{3}He to high energies preferentially takes place at the flanks of solar eruptions comprising both the impulsive flare and the CME. Remarkably similar patterns can be found also in the earlier observed 24 March 1991 event. These are empirical findings, largely independent of current or future interpretations.

3.2. SOLAR ORIGINS OF ^{3}He

It is generally accepted that low-energy, $\sim$ 1 MeV nucleon^{-1}, ^{3}He-rich events are produced in impulsive solar flares, in close association with acceleration of 2–100 keV electrons (Lin, 1985; Reames, Rosenvinge, and Lin, 1985). The sites of the flares associated with low-energy ^{3}He-rich events typically fill the region ±30° in solar longitude around W60° where the flare particles have easy and rapid access into the interplanetary field tube connected to the near-Earth spacecraft (e.g., Kocharov and Kocharov, 1984, Figure 31 therein). This seems contrary to what we observe in the high-energy range. A study of an individual high-energy ^{3}He-rich might even lead to the conclusion that a progenitor flare of the high-energy ^{3}He-rich event is not clear, because the most prominent flare is distant in the terms of both heliocentric angle and time. However, it is important that similar delays are present in all the high-energy ^{3}He-rich events observed (Table II). Furthermore, in the case of the strongest event, 29 October 2000, an interplanetary type II burst explicitly links the dominant flare, the ^{3}He event, and the magnetic enhancement (shock) observed at 1 AU (Torsti *et al.*, 2002). These facts justify the flare-SEP association, which, however, is very different from what one might expect based on the previous, low-energy ^{3}He observations.

Mason, Mazur, and Dwyer (1999) found that ^{3}He remnants from impulsive events are present on a majority of the days and suggested that this 'reservoir' may therefore be a source population that is available for further acceleration by interplanetary shocks, thereby leading to the moderate ^{3}He enhancements observed on board ACE in the energy range $\sim$0.5–2 MeV nucleon^{-1}. However, the high-energy ^{3}He rich events observed on board SOHO, with extremely high ^{3}He/^{4}He, are very rare and clearly associated with a recent, strong impulsive solar flare, which therefore seems the most plausible source of the seed ^{3}He population rather than apparently less intensive remnants of old events. The high-energy ^{3}He-rich events make up a new kind of hybrid SEP events, possessing the impulsive-type composition and the gradual-type time-profiles. Recently, Kocharov and Torsti (2002) summarized SOHO observations of hybrid events and emphasized a dependence of SEP events on the history of the particular solar eruption, which comprises not only the interplanetary shock but also the corresponding CME lift-off/aftermath processes in solar corona and the flare directly associated with the CME. The impulsive flare directly involved in the SEP-accelerating eruption is the most likely progenitor of pre-accelerated ions in the high-energy ^{3}He-rich events observed on SOHO. Thus, in the sense of the seed population history, our interpretation is alternative to that by Mason, Mazur, and Dwyer (1999), despite both concepts suggesting that seed populations for interplanetary shock acceleration come from flares. However it is also possible that the moderately rich events with ^{3}He/^{4}He $\sim 4\%$ (most of the ACE events) and the extremely rich events with ^{3}He/^{4}He $> 20\%$ (present SOHO events) have a different pre-acceleration history.

3.3. INTERPLANETARY RE-ACCELERATION

The impulsive solar flare may supply a seed particle population for further acceleration at the interplanetary CME. The event length and slow time-profile development, especially in the 23 December and 29 October ^{3}He-events, support the interplanetary CME acceleration. Torsti *et al.* (2002) reported that during the October event, an associated type II radio burst was observed with the WAVES experiment on board WIND before and simultaneously with the ^{3}He-rich event. The dynamic radio spectrum suggests that the interplanetary shock wave was located at about 0.3 AU from the Sun during the onset of the particle event. The four-event average value of the delay between the dominant flare and the ^{3}He onset is about $\frac{2}{3}$ day (Table II), whereas the three-event average interval between the ^{3}He-event onset and the onset of the magnetic field enhancement is about $\frac{4}{3}$ day (Figure 3). The ratio of the average values of the delays, $\frac{2}{3} : \frac{4}{3}$, supports an idea that the CME re-acceleration becomes significant when the leading (shock) wave is at about $\frac{1}{3}$ AU from the Sun. The $\frac{2}{3}$ day delay may comprise (i) a time needed for the flare-accelerated ^{3}He to get access to the CME flank, (ii) the CME propagation time to the point in the interplanetary medium where Alfvén speed becomes small enough to make the shock acceleration mechanism effective, and (iii) the particle acceleration time at the shock.

There were also a number of solar phenomena observed close to the onset or close to the main rise of the ^{3}He particle events, well after the dominant X-ray flare. A gradual, class C5.8 flare and EIT eruptions were observed at around 16:57 UT on 18 June 1999, preceding the main rise of high-energy ^{3}He intensity by 1–2 hours (Section 2.2). Close to the main rise, there were also a number of radio bursts registered, including, in particular, metric type II. On 14 August 1999, a west limb CME was observed about 1.5 hour before the ^{3}He onset (Table III). Table III also shows that during the first half of 23 December 1999, few CMEs were detected with the LASCO coronagraph, preceding by about 6–9 hours the ^{3}He onset time at SOHO. An eruption beyond the west limb occurred on 29 October 2000 about 2 hours before the ^{3}He onset time. These and a number of additional eruptions had been observed before the ^{3}He peak intensities were achieved at SOHO. Recall that two successive shocks were registered *in situ* during the 24 March 1991 event (Krupp *et al.*, 1992). Note also a magnetic cloud that passed the Earth not long before the exceptionally strong ^{3}He-event of 29 October 2000 (Section 2.5). Recently, Gopalswamy *et al.* (2002) emphasized a role of successive, interacting CMEs in production of major SEP events. Though the ^{3}He-rich events are relatively weak, it cannot be ruled out that a kind of interplay between successive solar eruptions is important also for production of the high-energy ^{3}He-rich events reported in the present paper. In particular, the additional solar eruptions might assist in the acceleration of ^{3}He to unusually high energies. However, the most prominent association of the considered ^{3}He-events remains a strong, impulsive X-ray flare and CME, most likely a wide CME, driving a magnetic-field compression/shock wave in the interplanetary medium.

4. Conclusions

Our search for ^{3}He enrichment in the energy range 15–30 MeV nucleon^{-1} revealed 7 events with ^{3}He/^{4}He $> 20\%$. For the first time, the extremely high values of ^{3}He-to-^{4}He ratio are observed in the energy range above 15 MeV nucleon^{-1}. We identify these events as high-energy ^{3}He-rich events, a new type of hybrid SEP event.

In this paper, we carefully studied histories of four sufficiently intensive events observed during 1999–2000. Appearance of ^{3}He enhancement in the unusually high-energy range can be explained with the combination of two processes - the process injecting pre-accelerated ^{3}He-rich material into the interplanetary space and the process of re-accelerating particles at interplanetary CMEs. We have performed a search for potentially significant solar and interplanetary factors for appearance of high-energy ^{3}He-rich events. With statistics in hand, we have formulated a list that includes (i) a primary, strong impulsive X-ray flare and CME, (ii) an interplanetary shock/compression wave, (iii) additional solar eruptions, and (iv) a flank position of the particle detector in respect to the primary eruption. Similarities in the development of high-energy ^{3}He-rich events support a general idea that the SEP production depends on the history of the entire solar eruption.

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References

Anglin, H. D.: 1975, *Astrophys. J.* **198**, 733.

Blake, J. B., Kolasinski, W. A., Fillius, R. W., and Mullen, E. G.: 1992, *Geophys. Res. Lett.* **19**, 821.

Bougeret, J.-L., Kaiser, M. L., Kellogg, P. J., Manning, R., Goetz, K., Monson, S. J., Monge, N., Friel, L., Meetre, C. A., Perche, C., Sitruk, L., and Hoang, S.: 1995, *Space Sci. Rev.* **71**, 231.

Brueckner, G. E., Howard, R. A., Koomen, M. J. Korendyke, C. M., Michels, D. J., Moses, J. D., Socker, D. G., Dere, K. P., Lamy, P. L., Llebaria, A., Bout, M. V., Schwenn, R., Simnett, G. M., Bedford, D. K., and Eyles, C. J.: 1995, *Solar Phys.* **162**, 357.

Cane, H., Reames, D. V., and von Rosenvinge, T. T., 1991, *Astrophys. J.* **373**, 675.

Chen, J., Guzik, T. G., and Wefel, J. P.: 1995, *Astrophys. J.* **442**, 875.

Clayton, E. G., Guzik, T. G., and Wefel, J. P.: 2000, *Solar. Phys.* **195**, 175.

Delaboudinière, J.-P., Artzner, G. E., Brunaud, J., Gabriel, A. H., Hochedez, J. F., Millier, F., Song, X. Y., Au, B., Dere, K. P., Howard, R. A., Kreplin, R., Michels, D. J., Moses, J. D., Defise, J. M., Jamar, C., Rochus, P., Chauvineau, J. P., Marioge, J. P., Catura, R. C., Lemen, J. R., Shing, L., Stern, R. A., Gurman, J. B., Neupert, W. M., Maucherat, A., Clette, F., Cugnon, P., and van Dessel, E. L.: 1995, *Solar Phys.* **162**, 291.

Desai, M. I., Mason, G. M., Dwyer, J. R., Mazur, J. E., Smith, C. W., and Skoug, R. M.: 2001, *Astrophys. J.* **553**, L89.

Dietrich, W. F.: 1973, *Astrophys. J.* **180**, 955.

Ermakov, S. I., Kontor, N. N., Lyubimov, G. P., Pavlov, N. N., Tulupov, V. I., Chuchkov, E. A., and Shcherbovskij, B. Ya.: 1993, *Izv. Ross. Akad. Nauk, Ser. Fiz.* **57**, No. 7.

Gopalswamy, N., Yashiro, S., Michalek, G., Kaiser, M L., Howard, R. A., Reames, D. V., Leske, R., and von Rosenvinge, T.: 2002, *Astrophys. J.* **572**, L103.

Hovestadt, D., Hilchenbach, M., Bürgi, A., Klecker, B., Laeverenz, P., Scholer, M., Grünwaldt, H., Axford, W. I., Livi, S., Marsch, E., Wilken, B., Winterhoff, H. P., Ipavich, F. M., Bedini, P., Coplan, M. A., Galvin, A. B., Gloeckler, G., Bochsler, P., Balsinger, H., Fisher, J., Geiss, J., Kallenbach, R., Wurz, P., Reiche, K.-U., Gliem, F., Judge, D. L., Ogawa, H. S., Hsieh, K.C., Möbius, E., Lee, M. A., Managadze, G. G., Verigin, M. I., and Neugebauer, M.: 1995, *Solar Phys.* **162**, 441.

Hsieh, K. C. and Simpson, J. A.: 1970, *Astrophys. J.* **162**, L191.

Hudson, H. S. and Cliver, E. W. J.: 2001, *Geophys. Res.* **106**, 25199.

Kocharov, L. G. and Kocharov, G. E.: 1984, *Space Sci. Rev.* **38**, 89.

Kocharov, L. G., Lee, J. W., Wang, H., Zirin, H., Kovaltsov, G. A., and Usoskin, I. G.: 1995, *Solar Phys.* **158**, 95.

Kocharov, L. and Torsti, J.: 2002, *Solar Phys.* **207**, 149.

Krupp, N., Keppler, E., Fraenz, M., Korth, A., Witte, M., Moussas, X., Blake, J. B., Naidu, K., Quenby, J. J., and Woch, J.: 1992, *Geophys. Res. Lett.* **19**, 1255.

Lepping, R. P., Acuna, M. H., Burlaga, L. F., Farrell, W. M., Slavin, J. A., Schatten, K. H., Mariani, F., Ness, N. F., Neubauer, F. M., Whang, Y. C., Byrnes, J. B., Kennon, R. S., Panetta, P. V., Scheifele, J., and Worley, E. M.: 1995, *Space Sci. Rev.* **71**, 207.

Lin, R. P.: 1985, *Solar Phys.* **100**, 537.

Litvinenko, Yu. E.: 2000, *Solar Phys.* **194**, 327.

Mason, G. M., Mazur, J. E., and Dwyer, J. R.: 1999, *Astrophys. J.* **525**, L133.

Miller, J. A., Cargill, P. J., Emslie, A. G., Holman, G. D., Dennis, B. R., Larosa, T. N., Winglee, R. M., Benka, S. G., and Tsuneta, S.: 1997, *J. Geophys. Res.* **102**, 14631.

Naidu, K., Quenby, J. J., Keppler, E., Korth, A., Witte, M., Krupp, N., Fraenz, M., Blake, J. B., Mazuk, S., and Moussas, X.: 1992, *Geophys. Res. Lett.* **19**, 1259.

Reames, D. V., von Rosenvinge, T. T., and Lin, R. P.: 1985, *Astrophys. J.* **292**, 716.

Reames, D. V., Meyer, J. P., and von Rosenvinge, T. T.: 1994, *Astrophys. J. Suppl.* **90**, 649.

Reames, D. V.: 1995, *Rev. Geophys. Suppl.* **33**, 585.

Roth, I. and Temerin, M.: 1997, *Astrophys. J.* **477**, 940.

Solar Geophysical Data: 1999a, *NOAA Prompt and Comprehensive Reports* **660** part I, **664** part II.

Solar Geophysical Data: 1999b, *NOAA Prompt and Comprehensive Reports* **661** part I, **662** part I, **666** part II.

Solar Geophysical Data: 1999c, *NOAA Prompt and Comprehensive Reports* **666** part I, **670** part II.

Solar Geophysical Data: 2000, *NOAA Prompt Reports* **675** part I, **676** part I.

Torsti, J., Valtonen, E., Lumme, M., Peltonen, P., Eronen, T., Louhola, M., Riihonen, E., Schultz, G., Teittinen, M. Ahola, K., Holmlund, C., Kelhä, V., Leppälä, K., Ruuska, P., and Strömmer, E.: 1995, *Solar Phys.* **162**, 505.

Torsti, J., Kocharov, L., Laivola, J., Lehtinen, N., Kaiser, M. L., and Reiner, M. J.: 2002, *Astrophys. J.* **573**, L59.

Zank, G. P., Rice, W. K. M., and Wu, C. C.: 2000, *J. Geophys. Res.* **105**, 25079.