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ON PURPORTED OBSERVATIONS OF PARTIALLY IONIZED GALACTIC COSMIC RAYS

A. J. TYLKA,[1] P. R. BOBERG,[2] AND J. H. ADAMS, JR.
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5352
T. KLEIS
CSI Institute, George Mason University, Fairfax, VA 22030-4444
AND
R. BEAUJEAN
Institut für Reine und Angewandte Kernphysik, Christian-Albrechts Universität zu Kiel, D-24118 Kiel, Germany
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ABSTRACT

Galactic cosmic rays are generally believed to be bare nuclei, fully stripped of all orbital electrons during passage through several g cm^{-2} of interstellar matter. Over the years there have been numerous reports of so-called "below-cutoff" Fe-group cosmic rays, with momentum below the minimum required for a fully ionized particle to reach Earth's inner magnetosphere. These reports comprised just a few tens of ions, but stimulated much speculation about partially ionized Galactic cosmic rays, suggesting a nearby source of Galactic cosmic rays. In this Letter we compare these previous reports to new observations of below-cutoff Fe-group ions from passive track detectors exposed for nearly 6 years in low-Earth orbit aboard NASA's *Long Duration Exposure Facility* (*LDEF*) satellite. The *LDEF* fluxes are only a few percent of the previously reported fluxes. This comparison suggests that the flux of below-cutoff ions must be out of phase with the observed solar-cycle variation of other (nonsolar) cosmic-ray sources and/or must strongly increase with decreasing altitude in low-Earth orbit. Both of these features are inconsistent with the notion of partially ionized Galactic cosmic rays as the source of the observed below-cutoff ions.

Subject headings: acceleration of particles — atmospheric effects — cosmic rays

1. INTRODUCTION

Propagation through the Galaxy generally leaves Galactic cosmic rays (GCRs) fully stripped of orbital electrons (Letaw et al. 1985). However, GCRs from a relatively nearby source, such as interstellar ions accelerated by the expanding shock of a relatively nearby and recent supernova, are probably not fully stripped (Soutoul & Ptuskin 1991). First-ionization-potential biases (Meyer 1985) clearly suggest that ions in the cosmic-ray source material are less than fully stripped. Supernova shock acceleration is expected to leave these ionization states largely unchanged (Soutoul & Ptuskin 1991). Moreover, electron stripping during propagation is less effective in the neighborhood of the solar system than on average in the Galaxy: whereas the neutral hydrogen density in the "average" cosmic-ray propagation volume is estimated to be $n_H \sim 0.3$ atom cm^{-3} (Lukasiak et al. 1994), the solar system is embedded in a small cloud where the neutral hydrogen density is $n_H \sim 0.1$ atom cm^{-3}, which in turn is located near the edge of the "Local Bubble," which has $n_H \sim 0.01$ atom cm^{-3} and extends for $\sim$100 pc (Cox & Reynolds 1987). Other mechanisms for producing partially ionized GCRs, involving acceleration of interstellar ions at the heliospheric boundary shock, have also been suggested (Mitra et al. 1991).

In recent years there have been numerous reports (Krause 1986; Blazh et al. 1986; Biswas et al. 1990; Grigorov et al. 1991; Chenette et al. 1991; Dutta et al. 1993; Cooper et al. 1995) of below-cutoff Fe-group ions observed deep within Earth's magnetosphere, with energies of $\sim$20 to a few hundred MeV per nucleon. These observations, which are summarized in Table 1, were generally made at solar-quiet times, when there was no significant fluence of solar energetic particles (SEPs) in interplanetary space. The collection locations were generally inconsistent with those of geomagnetically trapped ions. Anomalous cosmic rays are singly ionized (Adams et al. 1991), but Fe-group elements are not expected in the anomalous component (Fisk, Kozlovsky, & Ramaty 1974) and have not been observed in the anomalous component in the outer heliosphere. Some reports also show an enhanced sub-Fe ($Z = 21$–25) to Fe ratio, with more than twice as many sub-Fe ions as observed in GCRs outside of the magnetosphere (Gagarin et al. 1990; Biswas et al. 1991). In most reports, the authors quoted for each ion an upper limit on the ionic charge Q which would have allowed the ion to reach the observation point from interplanetary space.

Several authors (Biswas et al. 1990; Grigorov 1992; Dutta et al. 1993) have pointed to these observations as possible evidence of partially ionized GCRs. In this *Letter*, we question that interpretation, based on new results from the *LDEF* satellite. We emphasize that we question only the interpretation—not the observations themselves, which are almost surely correct, since different groups using different detector techniques at widely separated times report comparable results.

2. THE *LDEF* OBSERVATIONS

LDEF was deployed into a circular 476 km, 28°.5 orbit on 1984 April 7 and was retrieved by the Space Shuttle on 1990 January 12. *LDEF*, which was 3-axis stabilized, carried several large experiments intended to investigate rare cosmic-ray species. These experiments used stacks of plastic track detectors, to determine the elemental identity of cosmic ray nuclei (within limited resolution) and to measure their energy (from

[1] TYLKA@CRS1.NRL.NAVY.MIL.
[2] National Research Council Post-Doctoral Research Associate.

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TABLE 1

COSMIC-RAY EXPERIMENTS FOR STUDYING BELOW-CUTOFF Fe-GROUP IONS

Satellite/Experiment	Detector Type[a]	Mission Dates	Operational Time (10^5 s)	Geometry Factor[b] (cm^2-sr)	Energy Range (MeV/nuc)	Orbit Inclination (deg)	Orbit Altitude (km)
Salyut-6/Astro-2[1]	2	1981 May 17-21	3.4	~3000	<400	51.6	~350
S81-1/ONR-602[2]	1	1982 May 28 - Dec 5	95.0[c]	~1	~50-200	96.3	180-270
Spacelab-1/1ES024[3]	2	1983 Nov 28 - Dec 8	6.4	~1500	~70-150	57	~ 250
Spacelab-3/Anuradha[4]	2	1985 Apr 29 - May 6	2.3	~960[e]	25-125	57	~370
Cosmos-2022/Kashtan[5]	1	1989 May 26 - Jun 11	11.0	~80	30-350	82	~300
CRRES/ONR-604[6,2]	1	1990 Jul 25 - 1991 Oct 12	198.7[d]	~3.5	250-450	18.2	323-33,575
LDEF/M0002[7]	3	1984 Apr 7 - 1990 Jan 12	1813.5	660	20-200	28.5	476[g]
LDEF/HIIS[8,9]	3	"	"	~2500[f]	45-1100	"	"
LDEF/A0015[10]	3	"	"	~200	160-600	"	"
SAMPEX/HILT[11]	1	1992 Jul 3 - present	...	~60	10-90	82	520-670
SAMPEX/MAST[12]	1	"	...	~14	30-200	"	"

[a] Detector types: (1) electronic detector systems with timing information; (2) plastic track detectors with movable sections to provide timing information; (3) plastic track detectors without timing information.

[b] Nominal geometry factor for Fe-group ions. In general, the actual geometry factor varies with energy.

[c] Based on solar-quiet days, 1982 Jul 29–Nov 16 (Cooper et al. 1995).

[d] Based on solar-quiet days, 1990 Sep 5–1991 Apr 22 (Chenette et al. 1991).

[e] Based on reported analysis of half of the detector area (Dutta et al. 1993).

[f] Includes only one-eighth of the available detector area. Also, only ~20% of the sheets in the detector stack have been scanned and measured for the results presented here.

[g] Orbit decayed during the last year of the mission. See text for details.

REFERENCES.—(1) Blazh et al. 1986; (2) Cooper et al. 1995; (3) Krause 1986; (4) Dutta et al. 1993; (5) Grigorov et al. 1991; (6) Chenette et al. 1991; (7) Jonathal 1993; (8) Kleis et al. 1994; (9) Tylka et al. 1994; (10) Wiegel et al. 1995; (11) Klecker et al. 1993; (12) Cook et al. 1993.

range in the detector). These experiments were completely passive, providing no direct information on when or where individual ions were collected.

Figure 1 shows a compilation of mission-averaged Fe-group fluxes from *LDEF*. The results come from (1) the University of Kiel's M0002 experiment, (2) NRL's Heavy Ions in Space (HIIS) experiment, and (3) the Köln-Siegen detectors in the A0015 experiment. These experiments, which are described in Table 1 and in more detail elsewhere (Jonathal, Beaujean, & Enge 1993; Adams et al. 1993; Wiegel et al. 1995, and references therein), have demonstrated modest elemental resolution, ranging from ~0.4 to ~1.0 charge units at Fe. The experiments had complementary look-out directions from the satellite. HIIS was mounted on the space-facing end of *LDEF*, with an unobstructed view of the sky and efficient particle detection down to zenith angles of ~70°. The M0002 and A0015 experiments had similarly large opening angles, but were mounted near the south- and westward-facing surfaces of the satellite, respectively, where they could observe particles arriving from the direction of lowest geomagnetic cutoff.

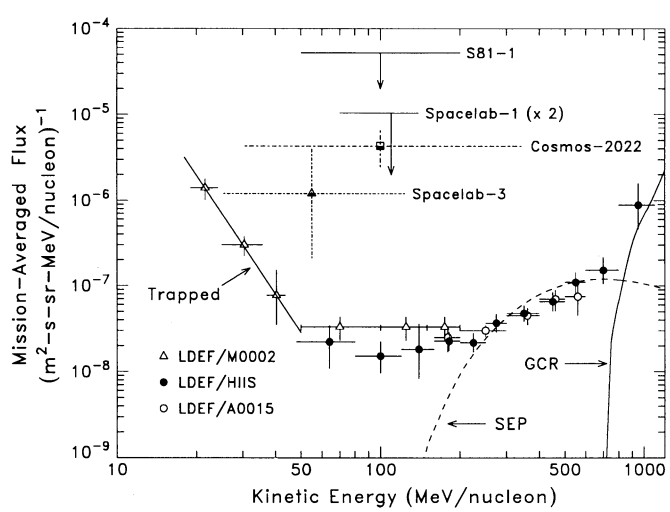

FIG. 1.—Mission-averaged Fe-group fluxes from *LDEF*. The A0015 and HIIS fluxes above 160 MeV per nucleon are for atomic numbers $25 \lesssim Z \lesssim 27$. The M0002 measurements and the HIIS data points below ~160 MeV per nucleon are for $Z \gtrsim 21$ ions. The curves show the expected contributions of SEPs and fully-ionized GCRs. (See text.) Also shown are fluxes of below-cutoff Fe-group ions observed within ±28°.5 latitude by other experiments. The *S81-1* and Spacelab-1 results are 90% C.L. upper limits. (The Spacelab-1 upper limit is multiplied by 2 for clarity in the plot.) The Spacelab-3 and *Cosmos-2022* points are uncorrected for possible detection inefficiencies and may thus underestimate the actual flux.

Since the *LDEF* detectors provided no timing information, the origin(s) of these ions must be deduced from other characteristics of the data. The distribution of arrival directions indicates that Fe-group ions below 50 MeV per nucleon are trapped in the geomagnetic field (Jonathal 1993; Jonathal et al. 1993; Beaujean et al. 1994, 1995). In the highest energy bin, the observed flux is consistent with the expected flux of (fully ionized) GCRs (Nymmik et al. 1992) in the *LDEF* orbit. Fully ionized GCRs cannot account for the observed flux at lower energies, even after taking into account occasional severe cutoff suppression due to geomagnetic storms during the *LDEF* mission (Adams et al. 1993; Tylka et al. 1994, 1995; Boberg et al. 1995). At ~200–600 MeV per nucleon the observed Fe flux and spectrum is accounted for by the large SEP events of 1989 October (ibid.), provided that SEP Fe at these energies has the same mean ionic charge state ($\langle Q \rangle \sim 14$) as observed at lower energies (Luhn et al. 1984, 1987). The SEP origin of ions in this energy range is also confirmed by their

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composition, which shows a sub-Fe to Fe ratio on the order of a few percent, after correction for fragmentation in the detector. The arrival directions also show the large west-east asymmetry expected from Störmer theory.

The origin of the Fe-group ions observed on *LDEF* at ~50–200 MeV per nucleon has not yet been explained. The arrival directions suggest a mixture of nontrapped and trapped or quasi-trapped ions (Beaujean et al. 1994; Kleis et al. 1994). Some of these ions may be SEPs. *If* these ions came directly from interplanetary space, they must have had ionic charge $Q \lesssim 8$–10. Due to small statistics and limited resolution, the sub-Fe to Fe ratio has not yet been measured in this energy interval.

3. COMPARISON OF PREVIOUS REPORTS AND *LDEF* RESULTS

Most of the experiments in Table 1 were flown at higher inclinations than *LDEF*. But since these experiments had timing information, we could identify ions which were collected within $\pm 28^\circ.5$ latitude and compare the corresponding fluxes to the mission-averaged fluxes on *LDEF* (see Fig. 1).

The *S81-1* (Cooper 1994; Cooper et al. 1995) and Spacelab-1 (Krause 1986) experiments reported below-cutoff Fe-group candidates, but none within $\pm 28^\circ.5$ latitude, so only upper limits are shown in Figure 1. The Spacelab-3 experiment (Dutta et al. 1993) used a rotating stack of track detectors to provide timing information. The analysis used trajectory tracings through Earth's magnetic field to identify 11 candidates which the authors called "definite partially-ionized events." Of these 11, only one Fe ion was collected within *LDEF* latitudes. The *Cosmos-2022* experiment (Grigorov et al. 1991) employed ionization chambers and identified four below-cutoff Fe-group ions (1 Fe, 2 Mn, 1 Sc) within $\pm 28^\circ.5$ latitude. By comparison with Störmer theory, these ions were claimed to have $Q/Z < 0.25$.

Several other reports of below-cutoff ions are not included in Figure 1. Other experiments in $51^\circ.6$ orbits also suggested partially-ionized heavy ions (Gagarin et al. 1992) but lacked timing information. Another track detector experiment on *Salyut-6* in 1981 (Blazh et al. 1986) provided timing information and saw a fluence of below-cutoff Fe-group ions comparable to that observed on *Cosmos-2022* (Grigorov 1994). This detector was exposed inside the *Salyut-6* space station. The amount of shielding was poorly known, and the energies of the observed ions were not well determined. Three partially ionized Fe candidates were also observed on *CRRES* during solar-quiet periods (Cooper et al. 1995). The corresponding fluence appears roughly comparable to those reported by Spacelab-1, *Salyut-6*, Spacelab-3, and *Cosmos-2022*. But the geosynchronous-transfer orbit of *CRRES* makes it difficult for us to compare its results to observations in low-Earth orbits.

The Spacelab-3 and *Cosmos-2022* fluxes in Figure 1 are based on just five Fe-group ions. However, these five ions are the partially-ionized candidates with the lowest inferred ionic charge ($Q < 6$) and hence are most difficult to dismiss as due to uncertainties in the geomagnetic transmission. Moreover, these ions were collected in ~2 weeks by instruments with geometry factors smaller than or comparable to those on *LDEF*. The *LDEF* experiments easily could have confirmed the flux levels implied by these few ions. Instead, the Spacelab-3 and *Cosmos-2022* fluxes *exceed* the *LDEF* mission-averaged fluxes by a factor of ~50, even though the *LDEF* data contain both SEPs and trapped ions, which are claimed to be absent from the other experiments.

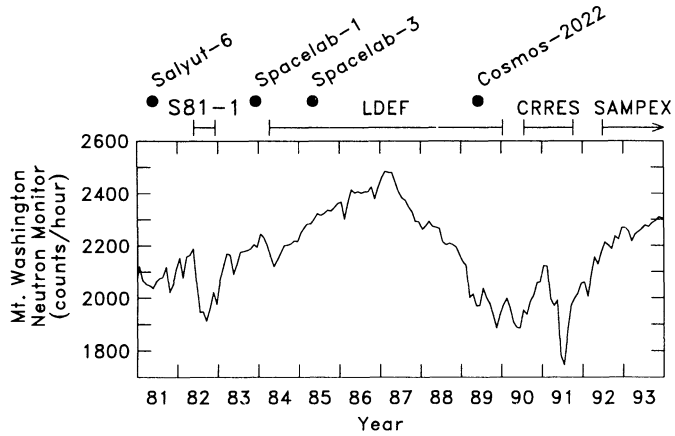

FIG. 2.—Observation dates of experiments for studying below-cutoff Fe-group ions, compared to the solar cycle as shown by the monthly averaged Mount Washington neutron monitor.

4. DISCUSSION

One obvious way to reconcile these other observations with the *LDEF* results is to posit that the below-cutoff ions were present at the previously reported flux levels for only a small portion of the *LDEF* mission. Such an explanation is entirely possible, but seems highly problematic for the notion of a Galactic origin for the observed particles. Figure 2 shows the time periods of the various observations, compared to the solar cycle, as tracked by the Mount Washington neutron monitor (Labonte 1994). The *LDEF* observations span a solar minimum, when solar modulation is most favorable for particles entering the heliosphere from interstellar space. But the other observations were made during periods of higher solar modulation. This too suggests that if the below-cutoff ions really did originate from outside the solar system, the mission-averaged *LDEF* flux should have been *higher*, not lower.

One additional point may be worth mentioning here. All of the other observations were made at altitudes of 250–370 km. For most of its 69-month mission, *LDEF* was at 476 km, but the orbit decayed rapidly in the final year. In the last month of the mission, *LDEF*'s altitude fell to ~370 km, and it was finally retrieved at ~330 km. If below cutoff Fe-group ions were collected by *LDEF* at the previously reported flux levels *only during this last month*, the contribution to the *mission-averaged* flux would roughly account for the otherwise unexplained flux at ~50–200 MeV per nucleon. Such a steep increase with decreasing altitude would also be inconsistent with the purported Galactic origin.

These reports of below-cutoff ions should be confronted soon by new data from *SAMPEX*, which has been flying in an 82° orbit at ~600 km since 1992 July. If the below-cutoff Fe-group ions are present at the *SAMPEX* orbit at the flux levels suggested by the earlier reports, the *SAMPEX* instruments should observe ~100 such ions per year. To date, published reports (Cummings et al. 1993) from *SAMPEX* cite only one $Z = 23$ ion collected by the MAST instrument at $1.45 < L < 2.65$ during the first 7 months of operation.[3] If

[3] A preliminary report (Mewaldt et al. 1994) from MAST has increased this estimate to 2 below-cutoff Fe-group ions (1 V, 1 Fe) in this L range in the first 18 months of observations. Another preliminary report (Klecker et al. 1994) from the *HILT* instrument has also shown a few Fe ions which may be below cutoff, but none with apparent charge state $Q < 14$.

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SAMPEX does not confirm the earlier reports, a strong altitude dependence may remain as the only way to reconcile all of the observations. Such an altitude dependence would rule out a new Galactic component, but it might be explainable in terms of cosmic rays which have passed through a significant amount of atmosphere, in which they have lost energy, as well as sometimes fragmented and scattered. Such "albedo" might also account for the reported enhancement in the sub-Fe to Fe ratio.

Whether or not albedo can quantitatively explain these observations requires further study. Heavy-ion albedo, with a flat spectrum at $\sim$20–200 MeV per nucleon, has been reported at balloon altitudes (Blanford et al. 1972; Friedlander & Hoppe 1977), with a *lower limit* on the fluence which is only $\sim$1% of the below-cutoff fluences observed at $\sim$300 km. Kurnosova et al. (1977) observed that high-energy proton albedo at 200–300 km can exceed the albedo at balloon altitudes by as much as a factor of $\sim$20.

Mewaldt (1994) has recently noted that SEPs, solar-wind ions, and corotating-interaction-region (CIR) ions should be accelerated to higher energies by encounters with the heliospheric termination shock. The heavy-ion flux thereby produced is completely unknown. These ions could show a very unusual solar-cycle dependence, determined by variations in the seed population, conditions at the termination shock, and solar modulation. Mewaldt has suggested that such ions could account for at least some of the partially ionized candidates observed in low-Earth orbits. But the reported enhancement in the sub-Fe to Fe ratio is inconsistent with this scenario. Also, the reported below-cutoff ions include a large fraction of very low inferred charge states ($Q/Z < 0.25$) which have not been observed in SEPs, solar wind, or CIRs.

The *LDEF* data contain trapped ions, SEPs, and possibly albedo, but we may nevertheless use the observed fluxes to set mission-averaged upper limits on the flux of partially ionized Fe-group ions outside the magnetosphere during solar-quiet times. Using Nymmik et al. (1992) to estimate the mission-averaged exomagnetospheric flux, the *LDEF* results imply (at the 90% C.L.) that less than 0.3% of such ions at 50–200 MeV per nucleon have $Q \leq 6$; less than 0.4% of these ions at 200–500 MeV per nucleon have $Q \leq 10$.

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