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CHARGE STATES OF ENERGETIC PARTICLES FROM COROTATING INTERACTION REGIONS AS CONSTRAINTS ON THEIR SOURCE

J. E. MAZUR
The Aerospace Corporation, 2350 East El Segundo Boulevard, El Segundo, CA 90245; joseph.mazur@aero.org
G. M. MASON[1]
Department of Physics, University of Maryland, College Park, MD 20742; glenn.mason@umail.umd.edu
AND
R. A. MEWALDT
Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125; rmewaldt@srl.caltech.edu
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ABSTRACT

Since the discovery of large (factor of greater than 1000) enhancements of singly ionized helium in corotating interaction regions (CIRs), it has become clear that low charge state ions from interstellar neutrals or other heliospheric sources can be preferentially injected into the energetic particle population. The large enhancements in suprathermal and energetic He^+ suggest that low charge state ions may likewise affect the composition of CIR-related heavy ions such as C or Ne. Therefore, a key observational test of the contribution of pickup ions to the energetic particles associated with CIRs is their ionization state. We have used instrumentation on board the low Earth orbiting *SAMPEX* satellite, along with the geomagnetic cutoff technique, to investigate the ionization states of CIR heavy ions in the energy range 0.5–1.0 MeV nucleon^{-1}. In a sum of 14 CIR events, we find heavy-ion charge states similar to those of solar energetic particles from interplanetary shocks, with upper limits to the contribution of singly ionized particles on the order of a few percent of the total flux. We find that stripping in the interplanetary medium of singly ionized heavy ions energized in the CIR could not account for the observed high charge states. Thus, the high charge state material we observed must have originated in the bulk solar wind or its suprathermal tail.

Subject headings: acceleration of particles — interplanetary medium — solar wind — Sun: particle emission

1. INTRODUCTION

The interaction between a high-speed solar wind stream from a coronal hole and slower solar wind forms the dominant interplanetary structure during the decay phase of the solar cycle. The compression of slow wind ahead of the wind from a coronal hole can occur at any time during the solar cycle. However, it is more likely near solar minimum that the division of the solar structure between polar holes and equatorial streamers leads to corotating interaction regions (CIRs) that can last several solar rotations. In addition to the CIR plasma and magnetic field characteristics, enhancements of energetic particles up to ∼10 MeV nucleon^{-1} can occur as the CIR approaches a spacecraft in interplanetary space. The energetic particles associated with the compression region and forward and reverse shocks are the focus of this report.

Mason et al. (1999) recently reviewed the features of the energetic particles associated with CIRs. Measurements from many spacecraft over the range from ∼0.3 to 10 AU formed the basis for this observational picture, some of which we summarize as follows: (1) maximum particle intensity at reverse shocks at ∼4 AU and 20° heliolatitude; (2) mostly sunward flow of particles at 1 AU but with occasional significant non–field aligned anisotropies; (3) low-energy ions observed at 1 AU in the absence of shocks; (4) nearly solar system composition, except for enhanced He and C relative to O; (5) He/O, C/O, and Ne/O increase with increasing speed of the high-speed stream.

In the suprathermal energy range, Gloeckler et al. (1994) found that interstellar pickup H^+ and He^+ were the two most abundant suprathermal species in a CIR at ∼4.5 AU, implying higher injection efficiencies for pickup ions compared to those in the solar wind. As a possible source for the CIR heavy ions such as C, Mg, and Si, Gloeckler et al. (2000a) proposed that the pickup ions released from interplanetary dust within ∼2 AU of the Sun (the inner source; Geiss et al. 1995) might similarly be preferentially injected into the CIR acceleration process. Geiss et al. (1995) and Gloeckler et al. (2000a) suggested that the relatively high abundance of C relative to O in the inner source population (C/O ∼ 1.46) might naturally account for the often-observed overabundance of C in the energetic particles in CIRs at 1 AU.

Therefore, the key observational test of the contribution of pickup ions from the inner source or the interstellar source to the energetic particles in CIRs is their ionization state. Here we report measurements of the composition and ionization states of 0.5–1.0 MeV nucleon^{-1} ions in CIR-related particle events observed at 1 AU during the declining phase of solar cycle 22. We use instrumentation on board the *SAMPEX* satellite at 1 AU along with the cutoff rigidity technique to search for any contributions of highly rigid, singly ionized particles to the overall CIR energetic particle population. We find that while the average heavy-ion charge states in CIRs were slightly lower than those in

[1] Also Institute for Physical Science and Technology.

large solar particle events, the contribution of pickup ions to energetic C–Fe is at most a few percent. These limits are considerably less than the contribution of pickup He^+ in CIRs previously observed at 1 AU.

2. OBSERVATIONS AND CHARGE STATE ANALYSIS

2.1. *Instrumentation*

The ion observations presented here were made with the low Earth orbiting *SAMPEX* satellite launched on 1992 July 3 (Baker et al. 1993). The Low Energy Ion Composition Analyzer (LICA) is a time-of-flight mass spectrometer that measures ion composition and energy spectra from H to Fe over ~0.2–5 MeV nucleon^{-1} (Mason et al. 1993). It provided the ion measurements discussed below.

To infer the energetic particle charge states, we used the low Earth orbit of *SAMPEX* and the Earth's magnetic field as a rigidity filter. This technique has been used with *SAMPEX* to infer the ionization states of anomalous cosmic rays (e.g., Klecker et al. 1995) and solar energetic particles (SEPs; e.g., Leske et al. 1995; Mason et al. 1995). Briefly, as the *SAMPEX* orbit at 82° inclination crosses from the polar cap to lower latitudes, the increasing magnetic field strength keeps successively higher rigidity particles from access to the satellite. For the relatively low rigidities discussed here (~100–1000 MV), we use actual particle cutoffs rather than a model calculation to calibrate the cutoff rigidities. The method is sensitive to even highly rigid singly ionized particles and is limited only by the event intensity.

2.2. *Event Selection*

We surveyed the *SAMPEX* measurements at 0.5–1.0 MeV nucleon^{-1} from 1992 July to 2000 July for CIR-related particle events using the criterion that daily averaged fluxes of C/O were greater than 0.7. Since the energetic particle C/O ratio in CIRs increases with higher solar wind speed (Mason et al. 1997), our selection may have been biased toward higher speed streams. Even so, the criterion clearly separated the CIR-related particle events from impulsive flares and traveling shock-related events. Once selected, we examined each event to ensure that indeed the particle increase had no velocity dispersion and that it did occur in coincidence with a high-speed solar wind stream. We list in Table 1 the 14 most intense CIR-related intervals of the survey.

Recurrent high-speed streams occurred throughout the survey period, even in the maximum phase of solar cycle 22 (Dwyer et al. 2000). The most intense of the 14 events in Table 1, and the ones that contributed to ~75% of the fluence of the survey, occurred in 1994 January and February. Figure 1 shows the early 1994 interval in detail. Three high-speed streams (National Space Science Data Center Omni data) swept past 1 AU in the 34 day interval in Figure 1. The streams beginning on days 11 and 38 produced energetic particles, while the stream between these two was "empty" (e.g., Richardson et al. 1993). Ion intensities peaked within the high-speed streams, as is often observed at 1 AU (Richardson et al. 1993). These particle events were much less intense than typical events associated with coronal mass ejections (CMEs). For example, the peak intensity of 0.5–1.0 MeV nucleon^{-1} oxygen in these CIRs was only ~10% that of the CME event of 1997 November 6, whose charge states were also measured with the cutoff technique (Mazur et al. 1999). The relatively low particle intensities highlight the need to sum over as many CIR events as possible for this charge state study.

TABLE 1

TIME PERIODS FOR CIR CHARGE STATE ANALYSIS

Event Number	Start Time (UT)	Averaging Interval (hr)
1	1992 Dec 8 0:00	39
2	1993 Jan 3 7:00	41
3	1993 Mar 23 2:00	34
4	1993 Sep 13 2:00	21
5	1993 Nov 4 6:00	36
6	1993 Nov 22 7:00	95
7	1993 Dec 16 10:00	62
8	1994 Jan 11 7:00	108
9	1994 Feb 8 0:00	96
10	1994 Jul 15 12:00	58
11	1994 Aug 11 0:00	54
12	1994 Oct 3 9:00	87
13	1994 Dec 6 9:00	63
14	1995 May 30 12:00	60

2.3. *Cutoff Rigidity Analysis in CIRs*

In order to combine the 14 events of Table 1 for the cutoff rigidity analysis, we needed to address the time-dependent cutoffs due to the changing geomagnetic field during geomagnetic storms and the local-time dependence of the cutoffs. Corrections for these effects minimize the spread in latitude of the cutoffs, allowing us to add many events together, and decrease the uncertainty of the inferred charge states. In the CME-related cutoff analyses at ~1 MeV nucleon^{-1}, we measured the changing cutoffs of 19–27 MeV protons on an orbit-by-orbit basis (Mason et al. 1995; Mazur et al. 1999); since the protons had known rigidities, the method corrected for both local time and storm effects. In the case of the CIRs, there were few such high-energy protons because of the steeper energy spectra and lower event intensities. Thus, we needed an alternative correction technique.

In the CIR events, the peak particle intensities occur a day or two after the arrival of the high-speed stream at Earth. Therefore, in these CIR cases the rapid cutoff changes that roughly follow the disturbance (D_{st}) index at onsets of geomagnetic storms occurred *before* the intervals for charge state analysis. However, the levels of subsequent cutoff suppression were still different by several degrees from event to event. We corrected for the different suppressions by using a fit to the cutoffs of 19–27 MeV protons measured in CME-related events of the form

$$\Lambda' = \Lambda - D_{st}(1.57e - 04)(90 - \Lambda)^2 , \quad (1)$$

where D_{st} is the 3 hr disturbance index, Λ' is the adjusted cutoff invariant latitude, and Λ is the observed cutoff in a sum of the 1992 November and 1997 November CME events (Mason et al. 1995; Leske et al. 1995). At 70° invariant latitude, the correction shifted the cutoff upward by ~6° for a D_{st} of -100 nT; this was the largest level of geomagnetic activity and subsequently the lowest cutoffs of the events we surveyed (event 4). Equation (1) also ensured a 0° correction at the magnetic pole.

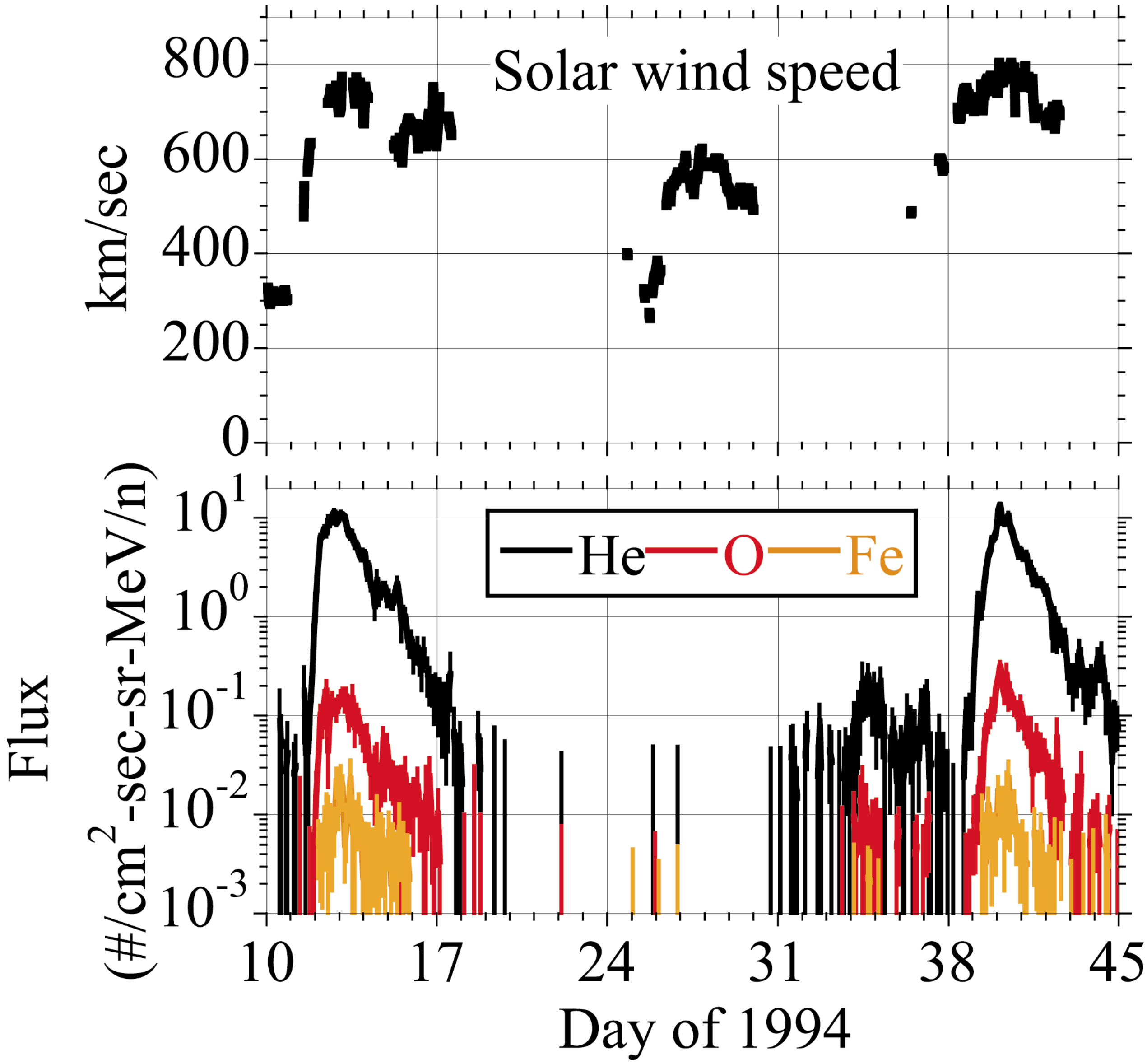

FIG. 1.—Solar wind speed and fluxes of 0.5–1 MeV nucleon $^{-1}$ ions at 1 AU for two rotations of a high-speed solar wind stream in 1994 January and February.

At the *SAMPEX* orbit, particles from interplanetary space with low rigidities ($\sim$100 MV) have access to lower latitudes on the night side because of propagation along the Earth's magnetotail (e.g., Faneslow & Stone 1972). We corrected for the different local times sampled in the 14 events of Table 1 by measuring the cutoffs of $\sim$1 MeV nucleon^{-1} He in north and south polar caps, after they were corrected for the D_{st}/storm effect. The cutoffs were well fitted with a circle of radius 21°.37 offset from the magnetic pole in the direction of 23:12 magnetic local time, similar to an offset circle determined for higher energy He (R. A. Leske 2000, private communication). The uncertainties of the offset-circle fit radius and local time were small ($\pm$0°.07 and $\pm$14 minutes, respectively) and therefore not propagated through the charge state analysis.

To show how well the local-time and D_{st} corrections removed the event-to-event variations in latitude, we plot in Figure 2 the profiles of 0.5–1.0 MeV nucleon^{-1} helium from the four most intense CIR events before we made the corrections (Fig. 2*a*) and after (Fig. 2*b*). In both figures we normalized the fluxes to the averages above 70°. If we determine the cutoff latitudes by finding the latitudes at which the polar averaged flux drops by 30%, we find that the adjustments decreased the event-to-event spread in cutoffs from $\sim$5° to $\sim$1°.5. Thus, while they did not remove *all* the variability, the corrections minimized the effects enough for us to proceed with the charge state analysis.

2.4. *Inferred Charge States*

To infer the charge states, we began with the corrected flux profiles of the most abundant species He, C, O, Ne, and Fe in the 14-event CIR sum. Figure 3*a* plots the fluxes of CIR-related He, O, and Fe at 0.5–1.0 MeV nucleon^{-1} in the 14-event sum versus corrected invariant latitude. We summed the fluxes in 1° wide bins in order to improve the statistics. To compare with the profiles in CME-related events, we show in Figure 3*b* the intensity profiles of the same species in the same energy range, but summed over the

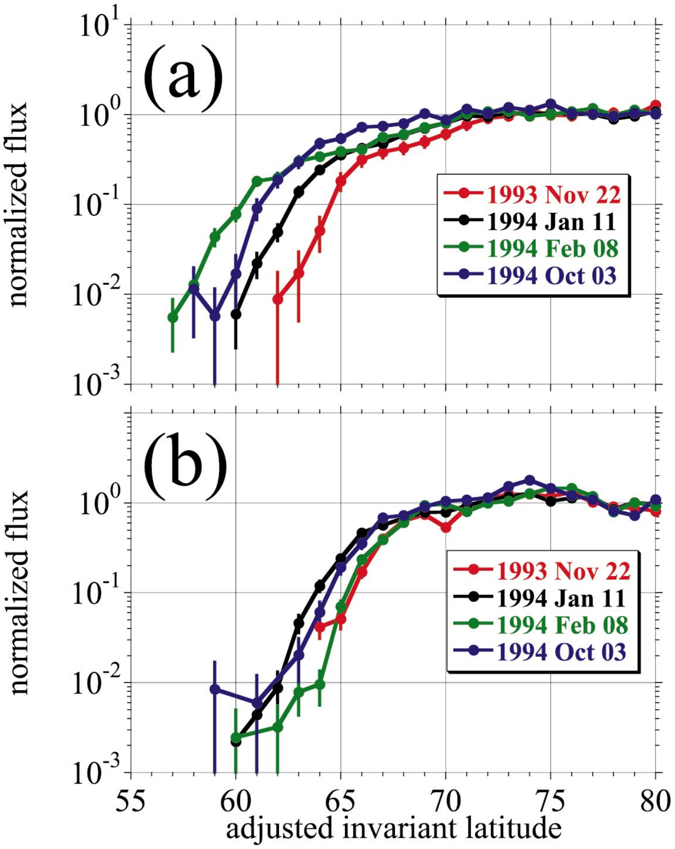

FIG. 2.—(*a*) Fluxes of 0.5–1 MeV nucleon^{-1} ions in the four most intense CIR events vs. adjusted invariant latitude, normalized to average flux above 70°. (*b*) Flux profiles of (*a*) vs. an invariant latitude scale that includes corrections for local time and geomagnetic activity.

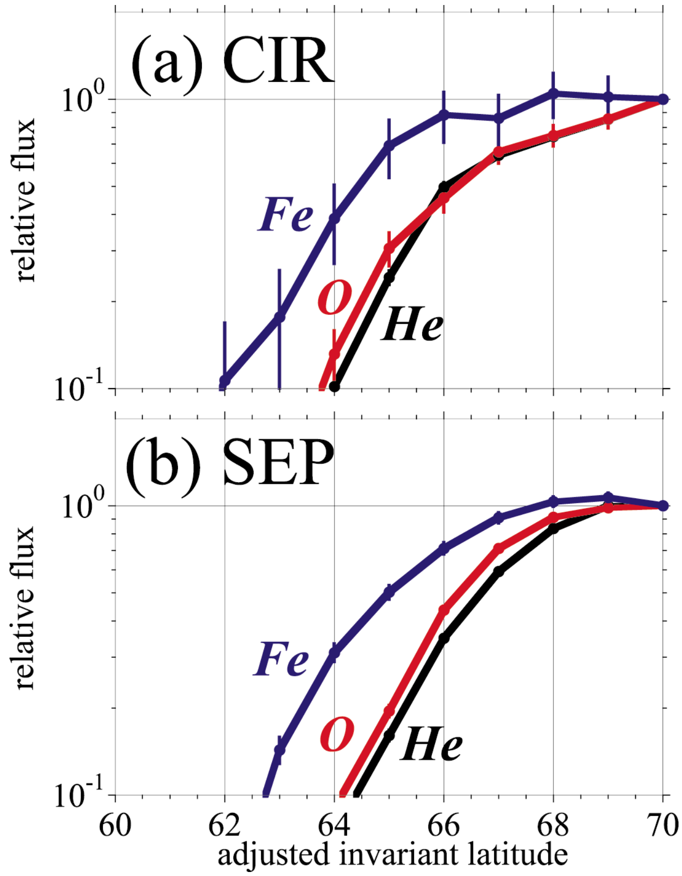

FIG. 3.—(*a*) Fluxes of 0.5–1 MeV nucleon^{-1} ions summed over 14 CIR events vs. adjusted invariant latitude, normalized at 70°. (*b*) Fluxes vs. latitude of a sum of all particle events that occurred in 1998.

entire year of 1998. In this case, CME-related events dominated the 1 AU fluxes. Comparing the two figures, we note that the relative ordering of the species was the same for CIRs and SEPs (Fe penetrated to lower latitude than O, and O lower latitude than He), implying that O was not fully stripped and Fe was even less so. We also note that the profiles in either case did not show any "steps" that would indicate a superposition of several charge states to the total flux.

Figure 4 compares the cutoff latitudes determined from a threshold of 30% of the average flux between 75° and 85° in the CIR and SEP populations (*arrows*). The relative separation and ordering of the cutoffs were not dependent on this choice of threshold. The solid curve in Figure 4 is the dependence of rigidity on invariant latitude measured in the 1997 November 6 SEP event (Mazur et al. 1999). We derived this calibration from cutoffs of SEP protons and helium using orbit-by-orbit corrections for the local time and geomagnetic storm effects (Mazur et al. 1999). We applied this calibration to the CIR analysis because it covered a wide rigidity range with good statistics and because it describes the observed low-energy cutoffs substantially better than those derived from particle tracing in models of the magnetic field (e.g., Smart et al. 1999). In Figure 4 we normalized the 1997 November, CIR, and 1998 SEP rigidity scales by assuming that all of the energetic He was fully stripped in all populations. Any contribution of He^+ would decrease the inferred charge states of the heavy ions by a proportional amount. We discuss this possibility below.

Note that Figure 4 shows the same ordering of cutoff latitudes in the two populations and that the CIR C, O, and Ne were slightly more rigid than the same species in the SEPs. Table 2 lists the ionization states in the CIR and SEP sums calculated from the observed cutoffs and calibration shown in Figure 4. We also compare these charge states

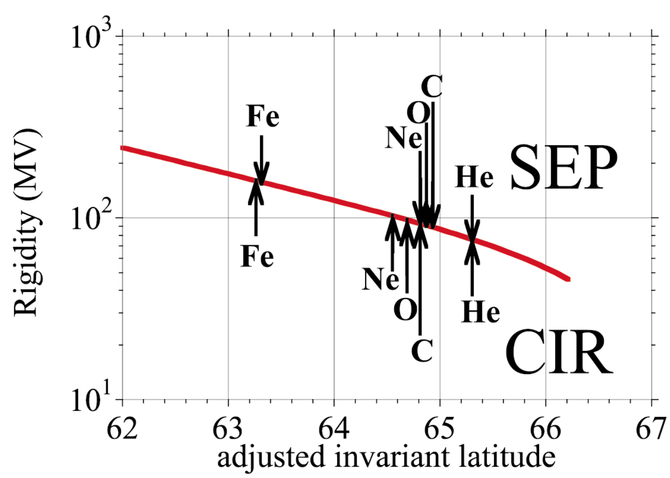

FIG. 4.—Calibration of the adjusted invariant latitude scale in terms of rigidity (*red curve*) with measured cutoff latitudes in the CIR sum and SEP sum.

TABLE 2

IONIZATION STATES IN CIR EVENT SUM AND SEP CHARGE STATE MEASUREMENTS

Element	CIRs[a]	SEPs		
		1998 Sum[a]	1992 Oct/Nov[b]	Luhn et al. 1985
He......	2.00 ± 0.12	2.00 ± 0.14	2.01 ± 0.10	...
C	4.83 ± 0.27	5.07 ± 0.33	6.08 ± 0.32	5.7 ± 0.29
O	6.12 ± 0.37	6.44 ± 0.37	7.61 ± 0.37	7.00 ± 0.35
Ne......	7.25 ± 0.25	8.25 ± 0.66	9.56 ± 0.46	9.05 ± 0.46
Fe	13.00 ± 0.48	13.20 ± 0.71	11.12 ± 0.26	14.9 ± 0.75

[a] 0.5–1.0 MeV nucleon $^{-1}$.
[b] 0.5–2.5 MeV nucleon $^{-1}$ (Mason et al. 1995).

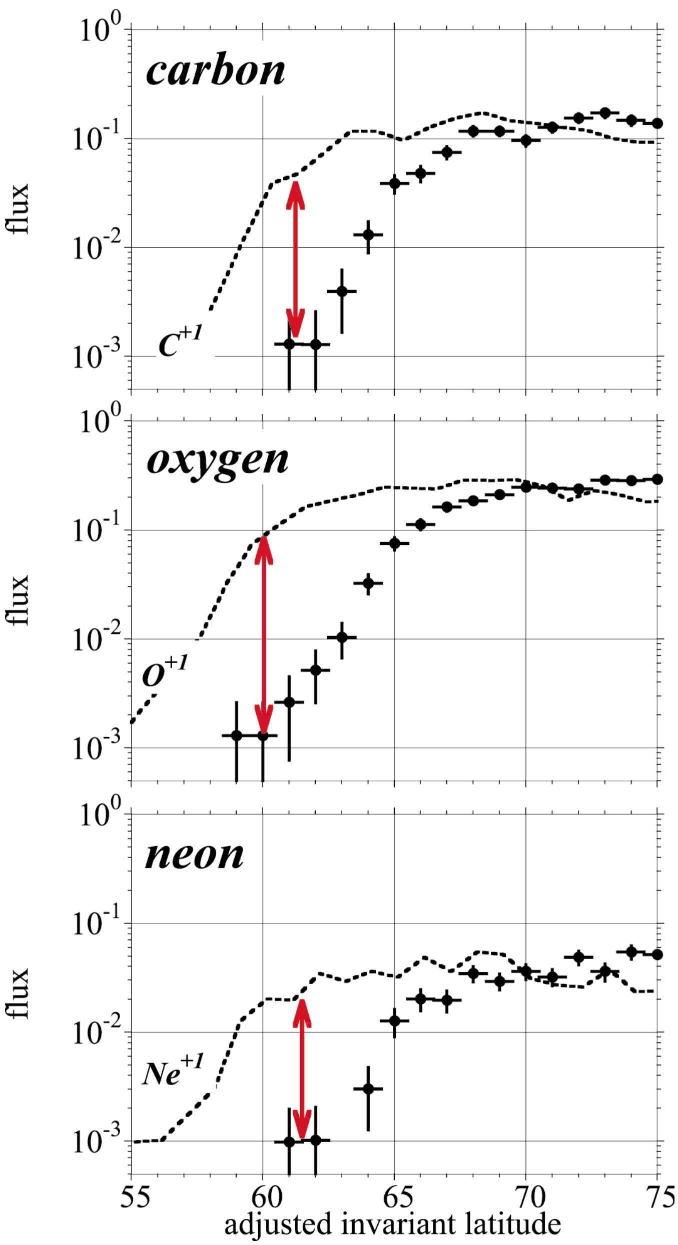

FIG. 5.—Observed flux vs. latitude profiles for CIR carbon, oxygen, and neon (*filled circles*) with inferred profiles for singly ionized species (*dashed curves*). Arrows show approximate factors at which the singly ionized fluxes might account for the lowest latitude points.

with previous measurements near ∼1 MeV nucleon^{-1} in Table 2.

2.5. *Limits to Singly Ionized CIR Particles*

Given the calibration of the invariant scale in terms of rigidity, we could then predict the cutoff latitudes for singly ionized particles of CIR-related He, C, O, Ne, and Fe. Figure 5 shows the profiles of singly ionized species if in each case 100% of C, O, and Ne ions had that particular charge state. Note that the profiles for the singly ionized cases are not calculations, so they have the same statistical fluctuations as the measurements. The figure also shows the observed profiles. The possible contributions of energetic C^+, O^+, and Ne^+ at ∼60° were approximately 2%, 1%, and 5% of the respective observed flux as shown by the vertical arrows in Figure 5.

3. DISCUSSION

Using the LICA instrument on the *SAMPEX* satellite we have inferred the charge states of energetic C, O, Ne, and Fe in a sum of 14 CIR-related particle events. Using the same method, we also inferred the average SEP charge states in a sum over many CME-related events in 1998 as a reference. We find that, irrespective of any detailed calibration of the cutoffs in terms of rigidity, the relative ordering and the relative separation of the CIR heavy-ion cutoffs were remarkably similar to those of the CME-related sample. This basic observation, along with previous SEP charge state measurements using the cutoff and electrostatic deflection techniques, rules out the possibility that singly ionized particles contribute significantly to the CIR C, O, Ne, or Fe fluxes at 1 AU.

We next used a calibration based on a previous CME-related event to calculate the observed charge states and the cutoff latitudes we would expect if the ions were singly or doubly ionized. The charge states of CIR-related ions were lower than that of the CME sample by a few percent. Because a factor of 6 in rigidity translated to over 5° in latitude, only the absolute flux of the 14-event sum constrained our estimate of the contributions of any highly rigid, singly or doubly ionized components. We would need a model of the cutoff profile at these low rigidities in order to derive a more detailed limit on their possible contribution. Nevertheless, those contributions must all have been less than a few percent of the flux of higher charge state material. We note that Möbius (2000) measured similarly low abundances (less than 10%) of singly ionized heavies in CIRs using electrostatic deflection instrumentation on the *ACE* spacecraft.

In deriving the rigidity calibration, we assumed that the He was fully stripped. It is the case that at 1 AU the He^+/He^{++} ratio is often $\sim$0.1 in CIR events (e.g., Chotoo et al. 2000). It is possible that the cutoff technique does not have the resolution to discern the 1° difference in cutoffs between He^+ and He^{++}, even with the D_{st} and local-time corrections (there was no "step" in the He profile). In that case, any contribution of He^+ lowers the observed mean He charge state and correspondingly all the charge states of the heavy elements by the same percentage, thus increasing the difference between the CIR average and SEP charge states.

We have explored the possibility that the CIR ions began as singly charged pickup ions that were subsequently stripped in the interplanetary medium, increasing their mean charge states to the values that we have observed. Mewaldt et al. (1996) and Jokipii (1996) applied the idea of stripping during acceleration at the solar wind termination shock to explain the observed fraction of multiply charged anomalous cosmic rays that originate as singly charged interstellar pickup ions. We can test this hypothesis for CIRs by calculating the mean stripping time of energetic oxygen ions from CIRs in the ambient solar wind. The mean time to go from a charge state of Q_a to Q_b in solar wind protons is given by

$$T_{ab} = \frac{1}{nv\sigma_{ab}} , \quad (2)$$

where n is the number density of the solar wind, v is the particle speed, and σ_{ab} is the cross section for stripping from Q_a to Q_b on hydrogen (Barghouty 2000). In Figure 6 we show the mean time in years for oxygen to be sequentially stripped from $Q = 1$ to the observed mean charge state of $Q \sim 6$ (according to Barghouty, Jokipii, & Mewaldt 2000 there is only a small probability of stripping multiple electrons in a single interaction). The calculations assumed a nominal distance of 2 AU for the CIR heavy-ion acceleration, corresponding to a mean solar wind proton density of 2 cm^{-3}, and used cross sections from Barghouty (2000) multiplied by a factor of 9/8 to convert from neutral to ionized hydrogen (A. F. Barghouty 2000, private communication). It is clear from Figure 6 that while stripping of 1 or 2 electrons is possible, it would take many years for singly charged oxygen to reach the observed mean charge state by this process. The timescales for stripping singly ionized carbon, nitrogen, and neon to their observed values are within a factor of $\sim$2 of that for oxygen. Thus, the long timescales for further ionization in the interplanetary medium rule out the possibility that the bulk of the observed CIR heavy ions began as singly ionized particles.

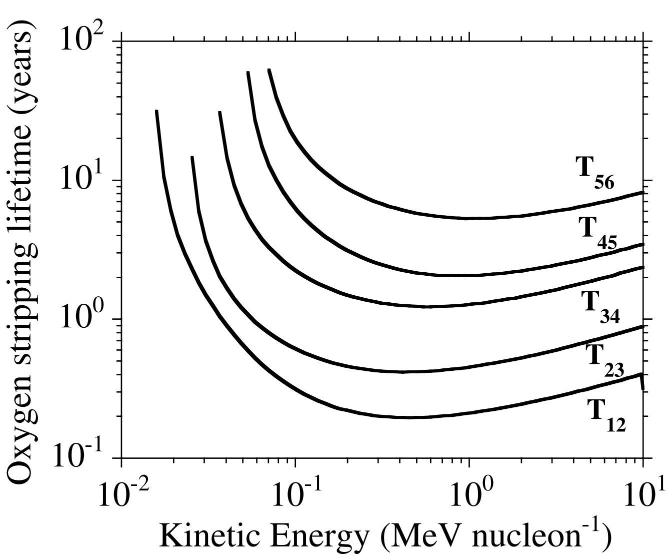

FIG. 6.—Calculation of the mean time to strip oxygen ions during acceleration and transport in the interplanetary medium for charge states ranging from $Q = 1$ to $Q = 6$. The calculations assumed a mean solar wind proton density of 2 cm^{-3}, appropriate to a distance of $\sim$2 AU.

The similar charge states of CIR and CME-related ions imply that the bulk solar wind or its suprathermal tail is the dominant source of energetic CIR ions at 1 AU, since the other candidate source populations (interstellar neutrals or inner source neutrals) would contribute material with low ionization states. The results of this study therefore directly address the possibility suggested by Gloeckler et al. (2000a, 2000b) that inner source pickup ions contribute as much as the suprathermal solar wind for further acceleration in CIRs within $\sim$2 AU. Gloeckler et al. (2000b) based their suggestion on the relative densities of the various components (solar wind, inner source pickup ions, and interstellar pickup ions) versus particle speed where the efficiency for injection into the CIR acceleration process may be high. The relative densities of these components depend on radial distance from the Sun, leaving the solar wind and inner source as the most likely candidates for sources of the CIR heavy ions near 1 AU. In the case of oxygen, Gloeckler et al. (2000b) noted that the solar wind, at charge state +6, would be the dominant source if the range of particle speeds over which the injection efficiency was nonzero included a large portion of the core of the solar wind distribution. Moving the injection threshold to higher speeds would increase the contribution of inner source pickup ions to the point where they would be comparable to or outnumber the solar wind. A low threshold speed may then indeed be necessary to account for both the high charge state heavy ions reported here as well as the $\sim$10% contribution of pickup helium observed at 1 AU that is from interstellar material (Chotoo et al. 2000). However, this leaves unexplained the differences in composition between CIRs and the other source populations cited above. Thus, it remains unclear how an acceleration mechanism using solar wind source material alone could account for the differences between CIR abundance features and other energetic particle populations in the heliosphere.

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