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THE FIRST OBSERVATION OF SULFUR IN ANOMALOUS COSMIC RAYS BY THE *GEOTAIL* AND THE *WIND* SPACECRAFTS

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ABSTRACT

The *Geotail* high-energy particle instruments have observed cosmic-ray particles in the energy range from 3 MeV n^{-1} to 150 MeV n^{-1} at 1 AU during the period 1992 September–1995 August. A remarkable enhancement of anomalous cosmic-ray (ACR) N, O, Ne, and C is observed during the period. A measurable enhancement of the sulfur flux below about 20 MeV n^{-1} was observed. This is the first evidence showing the existence of sulfur in the anomalous component. The flux increase of anomalous sulfur, with a first ionization potential (FIP) of 10.4 eV, is smaller than that of ACR carbon with an FIP of 11.3 eV and much smaller than those of high-FIP elements, which suggests that the fractions of neutral carbon and sulfur atoms are significantly low in the very local interstellar medium.

Subject heading: cosmic rays — ISM: general

1. INTRODUCTION

Anomalous cosmic rays (ACR) are observed as flux enhancements of the elements He, C, N, O, Ne, and Ar at low energies (a few tens of MeV n^{-1}) during the period of low solar modulation (Trattner et al. 1995; Lanzerotti et al. 1995; Mewaldt et al. 1993; Christian, Cumming, & Stone 1988; McDonald et al. 1974; Garcia-Munoz, Maison, & Simpson 1973; Hovestadt et al. 1973). The favored model explaining this enhancement was proposed by Fisk, Kozlovsk, & Ramaty (1974, hereafter the FKR model; Stone, Cummings, & Webber 1996; Cummings, Stone, & Webber 1994; FKR). As expected from the FKR model, the intensity of ACRs depends on the value of first ionization potential (FIP). Large enhancements of N, O, and Ne, with FIP values above 13 eV, are observed. On the other hand, low-FIP elements such as Mg, Si, and Fe, the FIP values of which are smaller than 9 eV, show no enhancement. The C flux is much smaller than that of O, as C has a low FIP value (11.3 eV). Thus, elements with an FIP value from 10 to 11 eV are key elements in the observation of ACRs for determination of the threshold element with the lowest FIP to be observed as anomalous. Therefore, it is important to know whether sulfur with an FIP of 10.4 eV can be observed, not only for studying the ACR composition, but also for determing the elemental abundances and the abundance ratio of neutral and ionized atoms in the very local interstellar medium (VLISM). The observation of sulfur, however, has not been reported, previously.

Until recent years, a geometric factor of particle instruments on-board satellites have been limited to be less than 1 cm^2 ster; the intensity of sulfur in ACRs is too low to be detected using such instruments. However, the *Geotail* spacecraft, launched in 1992 July, and the *Wind* spacecraft, launched in 1994 November, have several particle instruments with geometric factors substantialy greater than 1 cm^2 ster for observation of particles in the energy region from 1 MeV n^{-1} to 200 MeV n^{-1}. Recently, these particle instruments have observed sulfur ions in the cosmic rays in the “quiet times” period from 1992 September to 1995 August.

In this paper, we present new results on ACR elements, C, N, O, Ne, and S observed by three particle instruments on-board *Geotail* in the energy range of 5–200 MeV n^{-1} at 1 AU from 1992 September to 1995 August and observed by instruments on-board *Wind* in the energy range of 1.4–50 MeV n^{-1} at 1 AU from 1994 November to 1995 August.

2. SATELLITE ORBITS AND INSTRUMENTS

For the first two years after launch, *Geotail* flew in an elliptical orbit of apogee, 8 *Re*, and perigee, 210 *Re*. At the end of 1994 it moved to a new orbit of apogee, 8 *Re*, and perigee, 30 *Re*. The *Geotail* high-energy particle (HEP) experiment has three telescopes, HI, MI-1, and MI-2, each of which consists of a pair of two-dimensional position-sensitive silicon detectors and multilayer silicon detectors. The telescopes were designed on the basis of the well established $\Delta E \times E$ method for particle identification (Doke et al. 1994; Hasebe et al. 1993).

Since launch the *Wind* spacecraft has executed a complex orbit between Earth and the Lagrangian point (L1) between Earth and the Sun, spending most of its time in interplanetary space far outside Earth’s magnetosphere. The *Wind* EPACT experiment has four particle instruments, LEMT, APE, IT, and STEP (von Rosenvinge et al. 1995). All the instruments except for STEP consist of multilayer silicon detectors, using the $\Delta E \times E$ method for particle identification. In this analysis we use only the data obtained by the LEMT because low-

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TABLE 1

GEOMETRIC FACTORS AND ENERGY RANGES OF INSTRUMENTS ONBOARD *GEOTAIL* AND *WIND*[a]

Instruments	Geometric Factors (cm^2 ster)	Energy Range (MeV n^{-1})
Geotail:		
HEP-HI	45	18–210
HEP-MI1...........	5.3	4.5–50
HEP-MI2...........	31.5	6.5–120
Wind:		
EPACT-LEMT......	3.0 × 13	1.4–50

[a] HEP experiment instruments HI, MI-1, and MI-2 on-board *Geotail* and EPACT experiment instrument LEMT on-board *Wind*.

energy data which are below the energy range in HEP are needed in order to verify the existence of ACR sulfur. The overlapping energy range between the EPACT and the HEP instruments, moreover, is used to confirm absolute fluxes of various ions. Geometric factors for these telescopes are shown in Table 1 as well as their energy ranges.

3. OBSERVATIONS

The "quiet times" during the period from 1992 September to 1995 August were selected such that the particle intensity was less than 20 particles per 5 minutes for all times studied by MI-1, in order to exclude ions from solar flare events, traveling interplanetary shock events, corotating ion events, and other magnetospheric ion events.

Figure 1 shows the energy spectra for cosmic-ray N, O, and Ne (with high FIP) observed in the period from 1992 September to 1995 August. The fluxes above ∼50 MeV n^{-1}, which are the typical Galactic cosmic-ray component, are approximately proportional to the particle kinetic energy. In the energy below ∼50 MeV n^{-1}, however, the fluxes are steeply increasing. This enhancement of the flux is the anomalous component.

The spectra of C and Si are shown in Figure 2. Si, with an FIP of 8.1 eV, does not show an anomalous component, and the Si flux shows a monotonic decrease down to ∼12 MeV n^{-1} as expected from the FKR model. On the other hand, the flux of C with a middle FIP of 11.3 eV continues to decrease down to ∼30 MeV n^{-1} and then slightly increases at the lower energy, while the O flux below ∼50 MeV n^{-1} increases rapidly as shown in Figure 1.

Figure 3 shows the spectra of S and Fe observed in the period from 1994 November to 1995 August. The flux of Fe continues to decrease down to ∼20 MeV n^{-1}, suggesting that the influence of solar flare particles, traveling interplanetary shock events, and other ion events caused by solar and interplanetary activity are excluded sufficiently in the "quiet

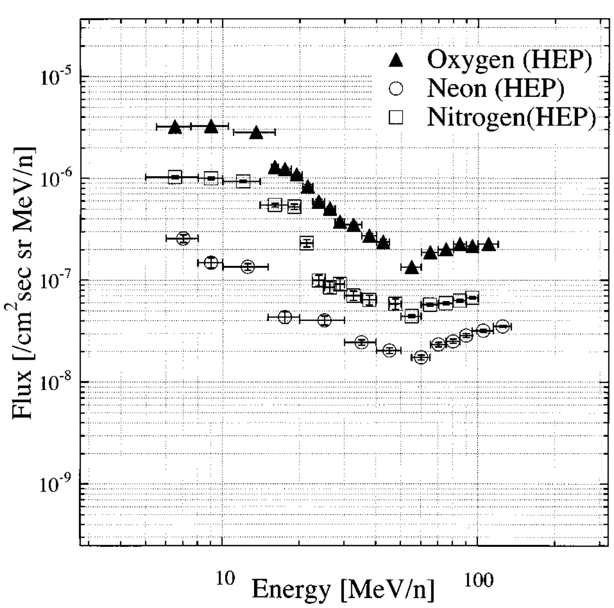

FIG. 1.—Differential energy spectra for N, O, and Ne during quiet times from 1992 September to 1995 August observed by the *Geotail*.

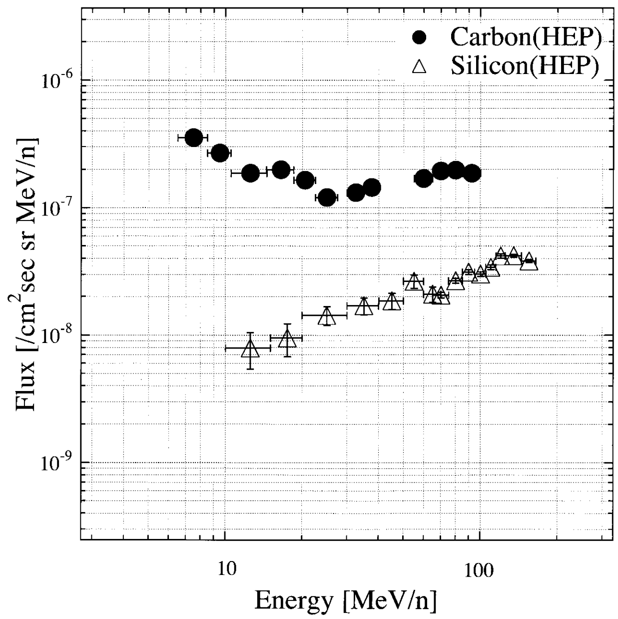

FIG. 2.—Differential energy spectra for C and Si during quiet times from 1992 September to 1995 August observed by the *Geotail*.

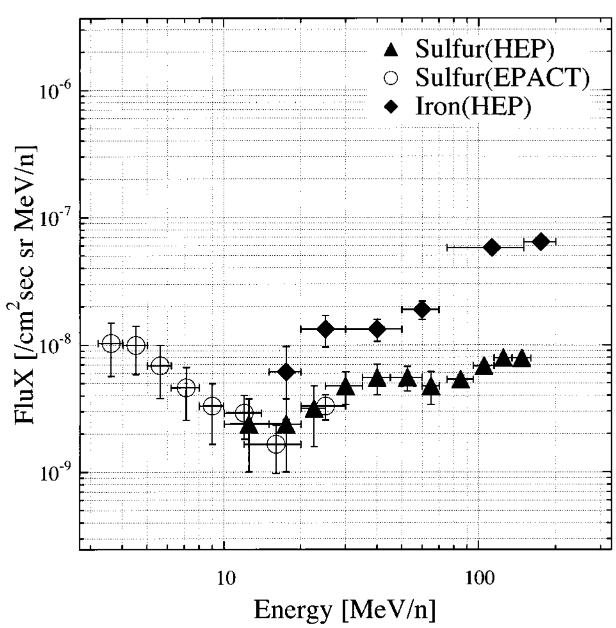

FIG. 3.—Differential energy spectra for S and Fe during quiet times from 1994 November to 1995 August observed by *Geotail* and *Wind*. Filled triangles are sulfur flux data from *Geotail*; circles are from *Wind*.

times" period we defined here. The flux of S in Figure 3 in the energy region above 9 MeV n^{-1} is measured by the HI and MIs (*filled triangles*) on *Geotail* and in the energy region below 15 MeV n^{-1} was measured by LEMT (*open circles*) on *Wind*. The range of energy between 9 MeV n^{-1} and 20 MeV n^{-1} overlaps both spacecraft. In the overlapping energy range, S observed by the instruments on-board both spacecrafts are in good agreement. The S fluxes above 30 MeV n^{-1} are consistent with that of the Galactic component. Around 15 MeV n^{-1}, the S flux begins to slightly increase with a decrease in energy. This increase below 15 MeV n^{-1} is thought to be caused by the ACR component as discussed in the next section.

4. DISCUSSION

The spectrum of Fe observed under the same condition and the same period of observation as that of S decreases down to ~20 MeV n^{-1} and shows no low-energy enhancement in its flux. This indicates that contamination by solar energetic particles and ion events caused by solar activity are almost completely excluded in the "quiet times" data. The flux of S below ~15 MeV n^{-1} in Figure 3 shows a slight increase, and the ratio of S to anomalous O is larger than the ratio of these two elements in the solar system in this energy region. This enhancement is the first evidence of the existence of S in the ACR composition. The FIP of S may be the approximate threshold potential at which an element is able to become an ACR. The fact that the flux of C, which has an FIP (11.3 eV) a little higher than that of S (10.4 eV), is enhanced in low-energy region while that of Si, which has a lower FIP (8.15 eV), is not, suggests that the threshold FIP is at least as small as 10.4 eV.

The flux ratio of elements to O is shown in Table 2. The ratios of Ne_{ACR}/O_{ACR} and Ne_{GCR}/O_{GCR} are almost the same. This result is reasonable because Ne and O are similarly accelerated and modulated in the solar heliosphere. On the other hand, the C_{ACR}/O_{ACR} ratio, about 0.1, is considerably lower than typical populations observed in the solar energetic particle where C/O about 0.4 (Webber 1982; Grevesse & Anders 1989) or in Galactic cosmic rays where C/O about 1.0 (Webber 1982; Grevesse & Anders 1989). This suggests that neutral C exists in the interstellar medium, but the amount is small. The S_{ACR}/O_{ACR} ratio, about 0.003, is also lower than typical abundances observed in solar energetic particles or in the Galactic cosmic rays where S/O is about 0.02 for each (Webber 1982; Grevesse & Anders 1989). This value is also less than that of C. Neutral S should exsist in the interstellar medium, but a large fraction of the S is ionized in the VLISM and the fraction of neutral atoms in S is less than that in C. This suggests that the ratio of neutral atoms to singly ionized particles depends on the FIP of each element and the lowest FIP element which can exist as a neutral atom is sulfur, according to this observation.

TABLE 2

FLUX RATIO OF ELEMENTS TO OXYGEN

Element	ACR	GCR
C..............	0.25	0.95
Ne	0.06	0.16
S...............	0.003	0.06

5. CONCLUSION

During the period from 1992 September to 1995 August, we observed the remarkable enhancement of anomalous cosmic-ray components O, N, Ne, and C. In addition to these observations, we found the enhancement of S at low energy, less than 20 MeV n^{-1}, for the first time from the observations on the *Geotail* and the *Wind* spacecraft, showing the existence of S as a component of the ACR. The fluxes of C and S with intermediate FIP increase slowly in the low-energy region below 20 MeV n^{-1}. It is concluded that large fractions of C and S are ionized in the VLISM, because the flux ratios of C/O_{ACR} and S/O_{ACR} are much smaller than one in solar energetic particles.

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REFERENCES

Christian, E. R., Cumming, A. C., & Stone, E. C. 1988, ApJ, 334, L77
Cummings, A. C., Stone, E. C., & Webber, W. R. 1994, J. Geophys. Res., 99, 11547
Doke, T., et al. 1994, J. Geomagn. Geoelectr., 46, 713
Fisk, L. A., Kozlovsky, B., & Ramaty, R. 1974, ApJ, 190, L35
Garcia-Munoz, M., Maison, G. M., & Simpson, J. A. 1973, ApJ, 182, L81
Grevesse, N., & Anders, E. 1989, AIP Conf. Proc. 183, Cosmic Abundances of Matter, ed. C. J. Waddington (New York: AIP), 1
Hasebe, N., et al. 1993, Nucl. Instrum. Methods Phys. Res., A325, 335
Hovestadt, D., Vollmer, O., Gloeckler, G., & Fan, C. Y. 1973, Phys. Rev. Lett., 31, 650
Lanzerotti, L. J., et al. 1995, Geophys. Res. Lett., 22, 3353
McDonald, F. B., Teegarden, B. J., Trainor, J. H., & Webber, W. R. 1974, ApJ, 187, L105
Mewaldt, R. A., et al. 1993, Geophys. Res. Lett., 20, 2263
Stone, E. C., Cummings, A. C., & Webber, W. R. 1996, J. Geophys. Res., 101, 11017
Trattner, K. J., et al. 1995, Geophys. Res. Lett., 22, 3349
von Rosenvinge, T. T., et al. 1995, Space Sci. Rev., 71, 155
Webber, W. R. 1982, ApJ, 255, 329