RHESSI OBSERVATION OF ATMOSPHERIC GAMMA RAYS FROM IMPACT OF SOLAR ENERGETIC PARTICLES ON 21 APRIL 2002

G. H. SHARE[1], R. J. MURPHY[1], B. R. DENNIS[2], R. A. SCHWARTZ[2],
A. K. TOLBERT[2], R. P. LIN[3] and D. M. SMITH[3]
[1]*E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375, U.S.A.*
[2]*NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.*
[3]*Space Sciences Laboratory and Dep't. of Physics, University of California, Berkeley, CA 94720, U.S.A.*

(Received 5 August 2002; accepted 10 September 2002)

Abstract. The RHESSI high-resolution spectrometer detected γ-ray lines and continuum emitted by the Earth's atmosphere during impact of solar energetic particles in the south polar region from 16:00 – 17:00 UT on 21 April 2002. The particle intensity at the time of the observation was a factor of 10 – 100 weaker than previous events when gamma-rays were detected by other instruments. This is the first high-resolution observation of atmospheric gamma-ray lines produced by solar energetic particles. De-excitation lines were resolved that, in part, come from ^{14}N at 728, 1635, 2313, 3890, and 5106 keV, and the ^{12}C spallation product at $\sim$4439 keV. Other unresolved lines were also detected. We provide best-fit line energies and widths and compare these with moderate resolution measurements by SMM of lines from an SEP event and with high-resolution measurements made by HEAO 3 of lines excited by cosmic rays. We use line ratios to estimate the spectrum of solar energetic particles that impacted the atmosphere. The 21 April spectrum was significantly harder than that measured by SMM during the 20 October 1989 shock event; it is comparable to that measured by *Yohkoh* on 15 July 2000. This is consistent with measurements of 10 – 50 MeV protons made in space at the time of the γ-ray observations.

1. Introduction

A moderate-sized solar energetic particle (SEP) event began shortly after the X1.5 solar flare from AR 9906 (S14 W84) that commenced at 00:43 UT and peaked at 01:51 UT on 21 April 2002 in soft X-rays. The flare was well observed by RHESSI which detected radiation up to about 400 keV; there was no evidence for nuclear line emission. A CME with a launch time of $\sim$01:15 and a speed of 2200 $\pm$ 300 km s^{-1} was observed by the LASCO instrument on SOHO (M. Andrews, private communication). Fast CME's such as this can produce shocks that accelerate the particles comprising the bulk of the SEP event. In Figure 1 we plot the integral fluxes of protons > 10 MeV observed by the GOES satellites from the 21 April 2002 particle event, in addition to those from the 19 – 20 October 1989 and 14 – 15 July 2000 events. The July particle event initially rose to an intensity ten times higher than that observed in October; however, the peak flux observed

Solar Physics **210:** 357–372, 2002.

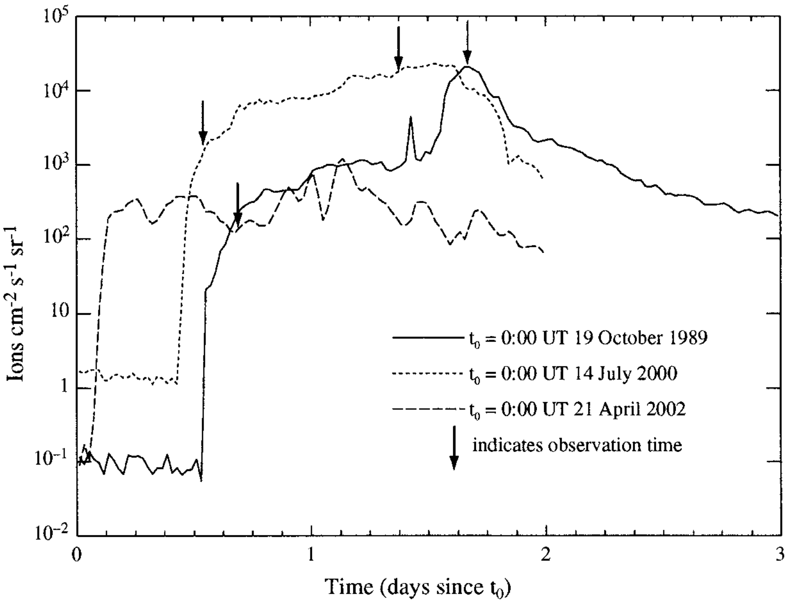

Figure 1. Integral fluxes of protons > 10 MeV observed by the GOES satellites during the 19 October 1989, 14 July 2000, and 21 April 2002 SEPs. The arrows depict times when atmospheric gamma rays produced by particle interactions were detected by SMM, *Yohkoh*, and RHESSI.

on 20 October from particles in the shock as it passed the Earth reached the level observed in the July event. The peak proton flux > 10 MeV from the 21 April 2002 event was at least a factor of 20 below the peak intensities observed from the earlier events.

Gamma-ray lines produced by solar energetic particle impact of the Earth's atmosphere were first detected by the moderate-resolution SMM spectrometer during the intense 20 October 1989 shock event (Share and Murphy, 2001). During this event the line intensities increased by over 2 orders of magnitude above the quiescent level. The quiescent line radiation is primarily from nuclei excited by neutrons produced in cosmic-ray collisions with atmospheric ^{14}N and ^{16}O (Ling, 1973). Details of the quiescent atmospheric positron-electron annihilation line at 511 keV were first provided by high-resolution measurements made by the HEAO 3 germanium spectrometer (Mahoney, Ling, and Jacobson, 1981). De-excitation line radiation from cosmic-ray impact was also observed by SMM (Letaw *et al.*, 1989) and HEAO 3 (Willett and Mahoney, 1992). Share and Murphy (2001) identified 19 resolved nuclear lines and the positron-electron annihilation line in the quiescent spectrum. Almost all of these lines appeared in the spectrum produced by the intense SEP event on 20 October. The nuclear lines were emitted from excited states of ^{14}N, ^{16}O, and various spallation products of high-energy interactions such as ^{11}B and ^{12}C. The *Yohkoh* gamma-ray spectrometer detected atmospheric radiation from the strong SEP event that reached earth beginning on 14 July 2000 following the

X5.7 ‘Bastille Day’ flare (Share *et al.*, 2001). This event was the third most intense proton event observed > 10 MeV. The resolution of the *Yohkoh* spectrometer was good enough to resolve only the ^{14}N 2.31 MeV de-excitation line and the ^{11}B/^{12}C complex near 4.4 MeV.

The arrows in Figure 1 denote the times when gamma rays were measured by SMM on 20 October 1989, by *Yohkoh* on 14–15 July 2002, and by RHESSI on 21 April 2002. These observations all were made as the satellites reached high magnetic latitude and viewed the atmosphere in the polar region where the low-energy protons are not impeded by the magnetic field and impact the earth’s atmosphere. On 21 April 2002 RHESSI observed the atmospheric glow of gamma-rays beginning at 16:05 UT as it approached its most southerly passage at a magnetic latitude of 48° S (magnetic cutoff $\sim$2 GV). At that time the SEP intensity was about two orders of magnitude below the intensities at the times of the gamma-ray observations by SMM on 20 October 1989 and by *Yohkoh* on 15 July 2000. In spite of this low particle flux RHESSI has made significant new measurements of atmospheric gamma-ray lines, which we discuss below.

2. Instrument Response to Orbital Background and Atmospheric Lines

The scientific objectives and design of the RHESSI instrument were described by Lin *et al.* (2000) and Smith *et al.* (2000). More details of the full design and instrument performance can be found in the current volume. RHESSI was launched on 5 February 2002 and has performed nominally since then. The spectral resolution of 8 of its germanium spectrometers has not degraded significantly during its 5 months of operation, although there are some differences in detector performance, especially at low energies. In our current analysis we sum data from the rear segments of 8 detectors as we are interested in the gamma-ray spectrum above a few hundred keV; we exclude data from detector 2 which has degraded resolution (Smith *et al.*, 2002).

The radiation observed by RHESSI is made up of several components and is highly variable within each orbit and from orbit to orbit. Due to weight constraints there is no anti-coincidence shield for rejecting charged particles, thus cosmic-ray protons and electrons that deposit energies in the RHESSI spectral range will be detected. Several passages per day through the intense proton belts irradiate the detector and spacecraft producing hundreds of gamma-ray lines. Wheaton *et al.* (1989) provided a detailed listing of the lines observed in the HEAO 3 germanium spectrometer. An excellent summary of the various backgrounds encountered in space missions can be found in the compendium of articles on the subject contained in the AIP publication ‘High-Energy Radiation Background in Space’ in which the Wheaton *et al.* (1989) article appeared. The instrument is also activated by the cosmic-ray flux that varies with magnetic latitude. This same flux generates the quiescent atmospheric gamma rays discussed in the Introduction that are also de-

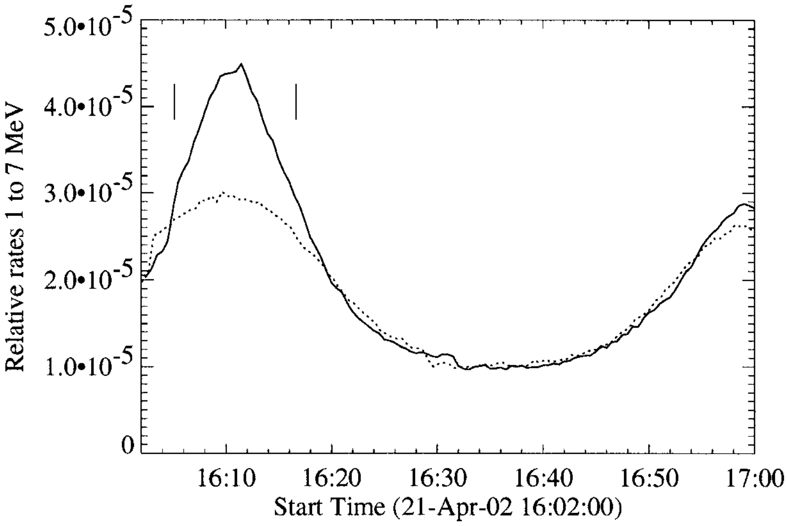

Figure 2. Rates observed in the 1 to 7 MeV band on 21 April 2002 (*solid line*) during the orbit when atmospheric gamma-ray lines were detected by RHESSI. Peak rates occurred when the satellite was at 48° S and 48° N magnetic latitudes. For comparison we plot the rates observed on 19 April shifted in time by + 640 s (*dotted line*). The spectrum of atmospheric gamma-rays was accumulated between the two lines.

tected. As RHESSI's orbit reaches magnetic latitudes near 50° it also can encounter precipitating electrons whose energies can reach MeV energies (Foat *et al.*, 1998).

In order to look for differences that may be related to an SEP enhancement in gamma-ray flux, we use the fact that the satellite returns to approximately the same physical location every 15 orbits. Typically we can use data taken on the previous and subsequent days shifted by an appropriate amount to estimate the background on a given day. However, there were insufficient data available at comparable times on 20 and 22 April. In Figure 2 we plot the relative rates observed in the 1 to 7 MeV band on 21 April 2002 (solid line), about 15 h after the X1.5 flare, at a time when the satellite reached high magnetic latitudes where the cosmic-ray intensity increases the rates significantly. (N.B. These and other rates presented in this paper are not absolute and have not been corrected for an energy-independent normalization error in the original data analysis software.) The rates are seen to peak near 16:10 and 17:00 UT when the satellite reached magnetic latitudes of ~ 48° S and ~ 48° N, respectively. For comparison, we also plot the rates (with a + 640 s shift in time) taken two days earlier on 19 April (dotted line) when the satellite reached magnetic latitudes ~ 1° higher.

There is a clear excess flux in the 1 to 7 MeV band on 21 April near 16:10 UT relative to the flux on 19 April, when the satellite was in the southern hemisphere; there was only a small increase over the 19 April flux 50 min later when RHESSI was in the northern hemisphere. The excess flux observed on 21 April is not likely to be due to precipitating electrons because the geomagnetic field was relatively

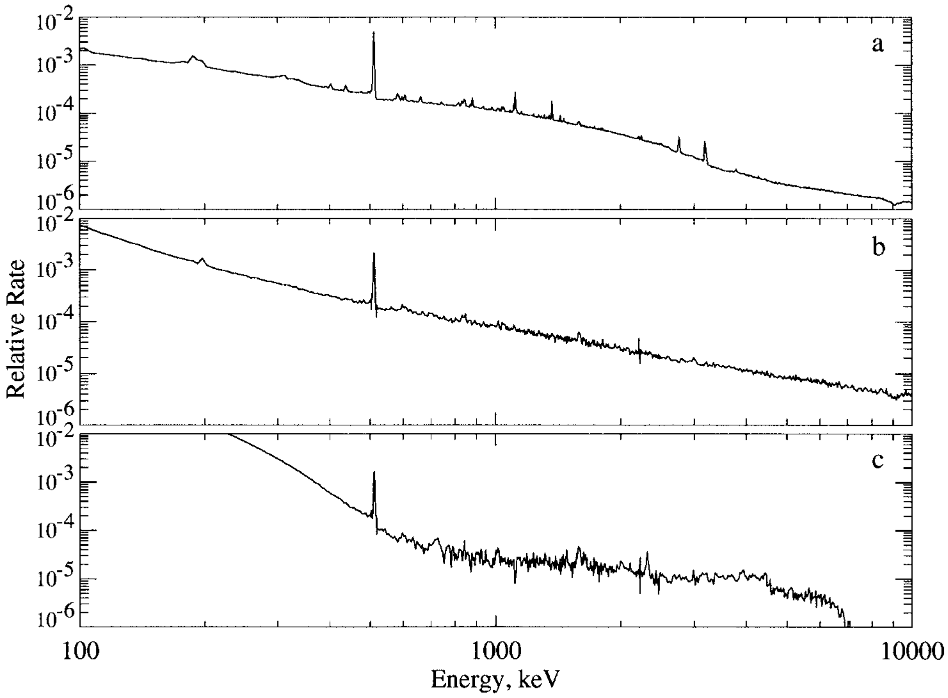

Figure 3. Comparison of three different RHESSI spectral accumulations. (a) Total background spectrum primarily from internal radioactivity, charged cosmic rays, and atmospheric radiation accumulated between 0–6 UT on 19 April 2002. (b) Spectrum primarily from charged cosmic rays, atmospheric radiation, and short-lived excited nuclei accumulated between 15:54:20 and 16:05:50 UT on 19 April after subtracting background at low magnetic latitude. (c) Gamma-ray spectrum from impact of SEP protons obtained by subtracting the data accumulated from 15:54:20 to 16:05:50 UT on 19 April from data accumulated from 16:05:00–16:16:30 UT on 21 April. (Note that a feature appearing in the spectra near 2.2 MeV is due to different energy binning around the neutron capture line and features near 1.6 MeV and 9 MeV are due to instrumental artifacts.)

quiet ($K_p = 1-$) at that time while it was significantly disturbed ($K_p = 6+$) on 19 April. We are interested in studying the spectrum accumulated near the peak between the two times marked by the lines in the figure, and comparing it with background spectra detected by RHESSI during a typical day. In Figure 3(a) we plot the spectrum from 200 keV to 10 MeV accumulated from 8 detectors in the first 6 hours of 19 April. The 511 keV annihilation line is the dominant feature and the power-law continuum extends up to at least 10 MeV. This continuum is primarily due to charged cosmic rays. Visible in the spectrum are over 120 narrow background lines that we show in more detail below. β-decay from radioactive species in the Ge detectors produces the curved continuum observed up to about 3 MeV.

In Figure 3(b) we show the typical spectrum of radiation accumulated at high magnetic latitudes, after subtracting the long-term radioactive background. This

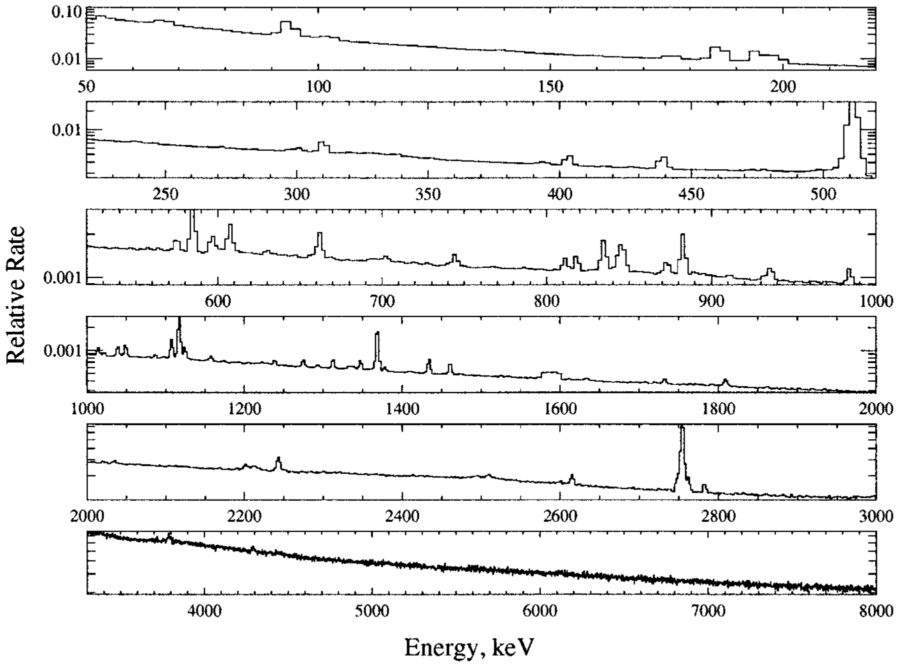

Figure 4. Detailed 24-hour background spectrum accumulated on 19 April with a resolution of 2.1 keV. (The broad feature below 1.6 MeV is an instrumental artifact.)

will be compared with the spectrum observed from the SEP event. The spectrum in Figure 3(b) was obtained by accumulating data taken at high latitude on 19 April, in the time interval between the two lines plotted in Figure 2, after subtracting background taken on both sides of the peak near the magnetic equator where the cosmic ray flux is lower. The annihilation line is once again the dominant spectral feature and sits above a power-law continuum from charged cosmic rays that extends to energies above 10 MeV. Most of the long-lived radioactive lines have been subtracted, but there are some residual background lines that we will discuss below.

The spectrum plotted in Figure 3(c) was obtained by subtracting the total 19 April spectrum between the times indicated by the lines in Figure 2 from the spectrum accumulated during the same relative interval on 21 April. This spectrum is markedly different from the others and is similar to the spectra observed by SMM and *Yohkoh* from the SEP events on 20 October 1989 and 15 July 2000. There is also an intense contribution at low energies that is likely to be due to precipitating electrons (the auxiliary particle detector observed an increase at that time).

In order to study the features of the three spectra plotted in Figure 3 in greater detail, we accumulated the data at higher spectral resolution. We plot a 24-hr background spectrum accumulated on 19 April 2002 at 2.1 keV resolution in Figure 4. There are over 120 gamma-ray lines in this spectrum, most of which have been

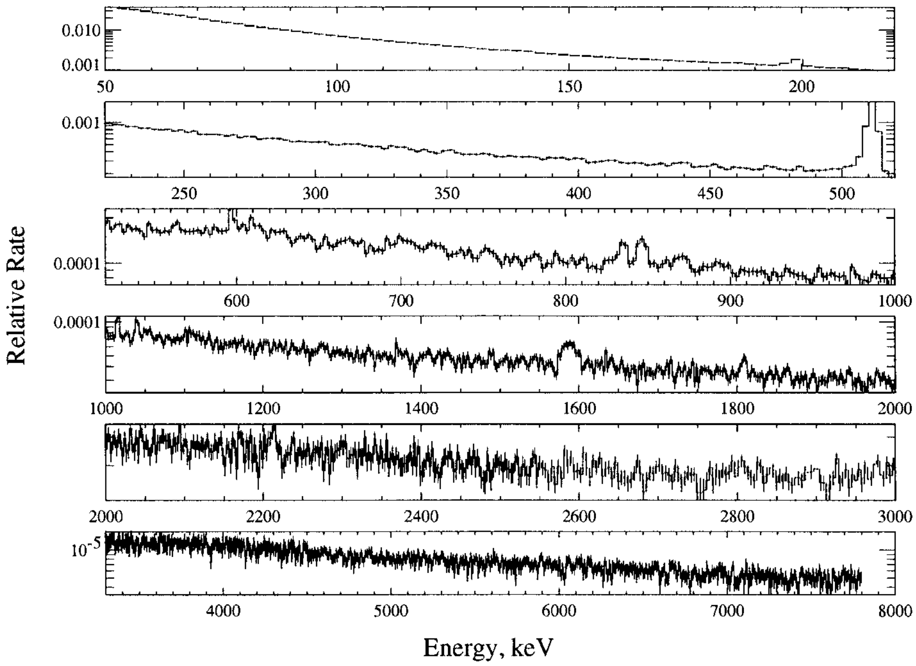

Figure 5. High-resolution spectrum of the background-subtracted data accumulated between 15:54:20 and 16:05:50 UT on 19 April 2002. Most of the radioactive lines have been removed by subtracting the spectrum accumulated at low magnetic latitudes. (2.5 keV bins to 2.5 MeV, 4 keV bins to 4.5 MeV, and 6 keV bins at higher energy; the broad feature below 1.6 MeV is an instrumental artifact.)

detected earlier using the study of the HEAO 3 background (Wheaton *et al.*, 1989) and an unpublished tabulation of TGRS/WIND data (Wiedenspointner, Ferguson, and Harris, private communication).

In Figure 5 we plot a high-resolution version of the background-corrected spectrum shown in Figure 3(b). The spectrum is dominated by a hard continuum due to the higher flux of charged cosmic rays > 45°S that deposit energy directly in the detectors and also produce bremsstrahlung from the Earth's atmosphere. Most of the long-lived lines shown in Figure 4 have been removed by the background subtraction. The strong annihilation line comes from radioactive nuclei and electromagnetic showers in the instrument, satellite, and Earth's atmosphere. There are also some residual lines evident from isotopes with short half lives that are not subtracted using data where the cosmic-ray background is lower. We have fitted these lines to identify their origins. The line at 198.3 keV is due to ^{71m}Ge that has a half-life of 20 ms and could be produced in an n,γ reaction on ^{70}Ge. There is a blend of lines near 600 keV that come from several excited states of ^{74}Ge, including lines at 595.9 and 608.4 keV from the first and second excited states, respectively. A strong line at 835 keV is likely to come from the first excited state of ^{54}Cr. Another strong line feature near 845 keV comes from a blend of the first excited

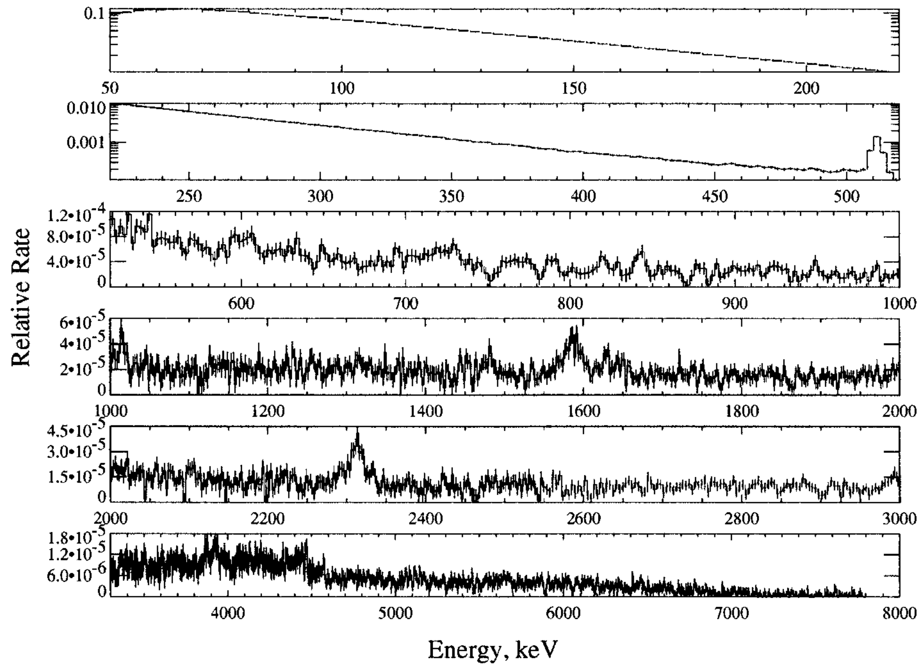

Figure 6. High-resolution spectrum of SEP-produced atmospheric line and continuum emission plotted in Figure 3(c). The spectrum was obtained by subtracting the total data accumulated from 15:54:20 to 16:05:50 UT on 19 April from data accumulated from 16:05:00–16:16:30 UT on 21 April. (The broad feature below 1.6 MeV is a data artifact.)

states of ^{27}Al and ^{56}Fe. The line near 1014 keV is from the second excited state of ^{27}Al, while an equally strong line near 1039 keV is likely from the first excited state of ^{70}Ge. The line near 1809 keV is consistent with the first excited state of ^{26}Mg, produced by an *n,pn* reaction on ^{27}Al. A broadened line feature appears centered near 2211 keV that is in part due to emission from the third excited state of ^{27}Al.

In Figure 6 we plot at high resolution the SEP-produced atmospheric spectrum on 21 April between 16:05:00 and 16:16:30 UT after subtracting background accumulated on 19 April. We first search for the same background features that were observed in the spectrum at high latitudes shown in Figure 5. There is no evidence for the line at 198.3 keV. Weak line features appear near 597 and 608 keV that are consistent with high-latitude background lines. A narrow line feature is evident near 843 keV that could be due to ^{27}Al (843.7 keV); however, there is no evidence for the ^{56}Fe line (846.8 keV). A second line from ^{27}Al may be present in the spectrum near 1015 keV but there is no evidence for the higher energy line at 2211 keV. There is also no evidence for the ^{26}Mg line at 1809 keV. The presence of any of these instrumental lines would be puzzling as we believe that the SEP protons can not penetrate the magnetosphere at a rigidities near 2 GV, where the satellite was positioned. The geomagnetic field was also much quieter on 21 April

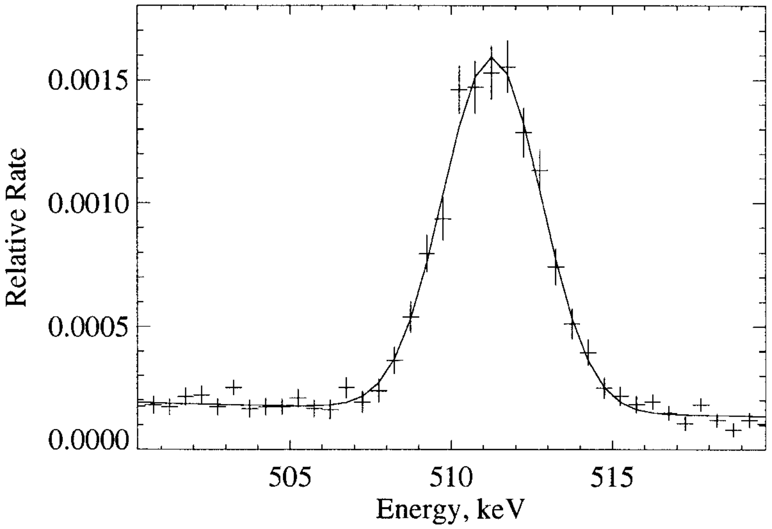

Figure 7. Fit to the 511 keV line observed during the SEP event.

than it was on 19 April when the background was accumulated. We also note that the possible line features discussed above are not significantly stronger than other fluctuations that appear in the spectrum between about 520 and 1000 keV.

3. Measurements of SEP-Produced Atmospheric Gamma-Ray Lines

In this section we specifically discuss line features associated with gamma rays produced by the SEP protons that impacted the Earth's atmosphere in the polar region and were observed remotely by RHESSI. We specifically will concentrate on the strong lines observed in the SMM measurement of the 20 October 1989 event (Share and Murphy, 2001). The annihilation line is the dominant feature in the spectrum. In Figure 7 we plot a fit to the RHESSI annihilation line. We have performed a χ^2 map to obtain the best fitting values for the energy and width; they are 511.3 ± 0.1 keV and 2.44 ± 0.14 keV (FWHM).

A weak broad feature appears above 700 keV in the RHESSI spectrum that is near the position of a line observed in the 20 October 1989 SEP event by SMM and attributed to ^{10}B (718 keV) and ^{14}N (728 keV). We have fit this feature with both a single line and with two lines having fixed energies at 718 and 728 keV. We plot the data and the latter fit in Figure 8. We have performed a χ^2 map to obtain the best fitting values for the energies and widths. For a single line, the energy is 723.0 ± 2.0 keV and width is 21.3 ± 5.2 keV (FWHM). The fit with two lines is slightly improved. The 718 keV line is about two times stronger than the 728 keV line. Its width (FWHM) is 24 ± 8 keV while the 728 keV line is probably less than about 15 keV wide.

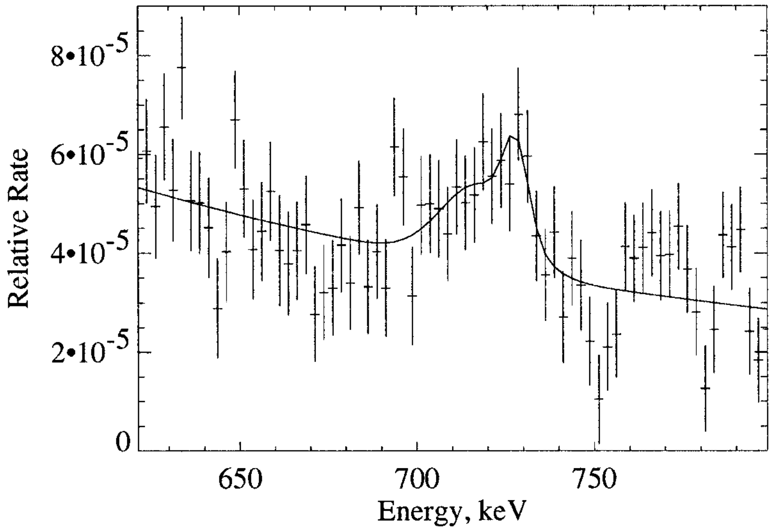

Figure 8. Fit to the ~720 keV line feature from the Earth's atmosphere produced by the SEP.

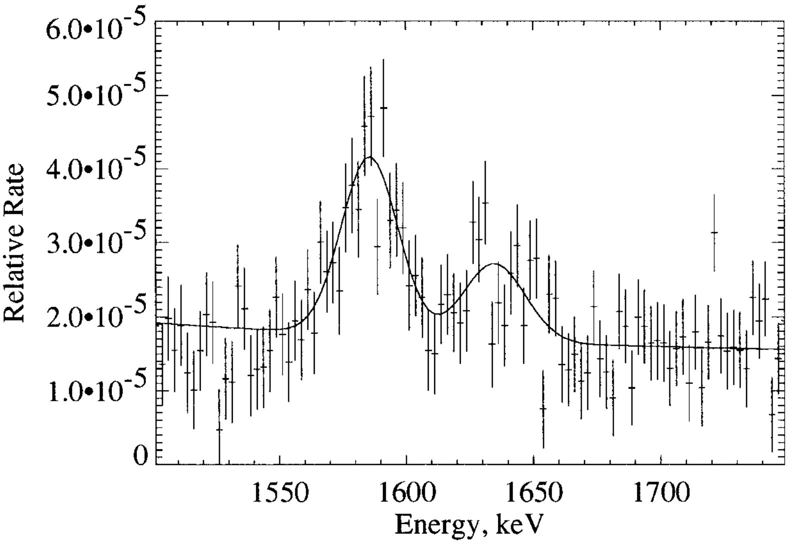

Figure 9. Fit to the 1630 keV ^{14}N line from the Earth's atmosphere produced by the SEP. In order to do this we also simultaneously fit the instrumental artifact with a Gaussian shaped line.

One of the strong lines in the SMM spectrum appears at 1630 keV and is associated with de-excitation of the 3948 keV level in ^{14}N to the first excited state. For this reason we have studied this region in more detail in the RHESSI spectrum. We plot the spectrum in this region in Figure 9. The dominant feature is an instrumental artifact that appears between 1550 and 1600 keV. There is evidence for a broadened line just above 1600 keV. We fit both the artifact and the atmospheric

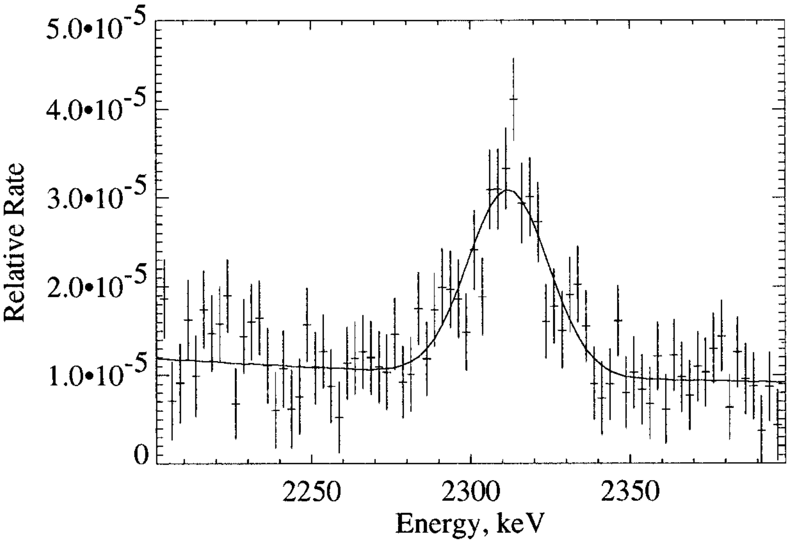

Figure 10. Fit to the 2313 keV ^{14}N line from the Earth's atmosphere produced by the SEP.

line with Gaussians and performed a χ^2 analysis in order to obtain the energy and width of the ^{14}N feature. The best fitting energy and width of the ^{14}N line are 1635.0 ± 3.0 keV and 30.0 ± 6.9 keV (FWHM), respectively.

The second most striking line in the atmospheric spectrum observed during the SEP event appears near 2310 keV. This is the location of the line that arises in the transition from the first excited state of ^{14}N to its ground state. In Figure 10 we plot the RHESSI spectrum and best fit to the data. Our χ^2 analysis produced a measured energy of 2312.5 ± 1.2 keV and width of 25.8 ± 3.9 keV (FWHM).

The energy range between 3500 and 7000 keV is quite complex. According to the SMM measurements, there may be at least 10 identifiable lines in this energy range. We plot the RHESSI spectrum in Figure 11. The features in the spectrum are generally complex and not easy to resolve. This is especially true at the highest energies where the efficiency of the instrument is rather low. There are three rather well-defined features in the spectrum, near 3900, 4420, and 5115 keV. These features have been identified in the SMM spectrum as primarily being due to transition from the 6204 to 2313 keV level (3890 keV) in ^{14}N, from ^{11}B (4444 keV) and ^{12}C (4439 keV) spallation products, and from transition from the 5106 keV level to the ground state in ^{14}N. In fitting the spectrum we included lines at 3900, 4180, 4420, 5115, 5830, 6133, 6350, and 7000 keV and used the full instrument response for an incident angle of 60°, that includes escape peaks and Compton continuum. We fixed the line energies and widths of some of the weaker features at the values found in the SMM observation. We show the best fit to the spectrum in the figure. We then performed a χ^2 analysis of lines near 3900, 4420, and 5115 keV to obtain measurements of their energies and widths. The derived energies of the lines are

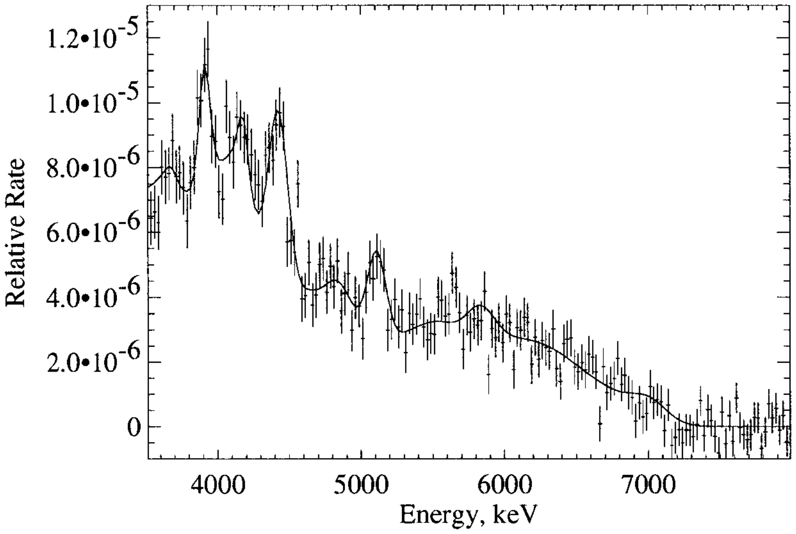

Figure 11. Fit to the RHESSI spectrum between 3500 and 8000 keV, including Gaussian lines near 3900, 4180, 4420, 5115, 5830, 6133, 6350, and 7000 keV.

3911.5 ± 8.5, 4422.0 ± 8.0 keV, and 5116.0 ± 12.0 keV, and their widths are 80.5 ± 13.8, 200 ± 16 keV and 157.6 ± 26.5 keV, respectively.

4. Summary and Discussion

A moderate-sized solar energetic particle event followed an X1.5 solar flare on 21 April 2002. RHESSI observed hard X-rays up to about 400 keV from the flare. About 16 hours after the flare RHESSI also detected gamma-ray lines emanating from the polar region in the southern hemisphere produced by the solar energetic particles impacting the Earth's atmosphere. In Table I we compare the integral fluxes of protons $>$ 10 MeV and flux ratios at the times of the detection of atmospheric gamma-rays for this and two other events. The SMM spectrometer (Share and Murphy, 2001) observed the October 1989 event and the *Yohkoh* GRS detector the event in July 2000 (Share *et al.*, 2001). At the time of the RHESSI observation, the proton flux was one to two orders of magnitude weaker than fluxes at the times of the previously detected atmospheric gamma-ray events.

In order to validate the RHESSI atmospheric-line detection during this relatively weak SEP event, we accumulated a 24-hr background spectrum two days before the flare. There are over 120 narrow lines and a β-decay continuum visible in the spectrum over a power-law continuum from charged cosmic rays that extends to at least 10 MeV (Figures 3(a) and 4). Most of the narrow lines have been observed previously by the HEAO 3 germanium spectrometer (Wheaton *et al.*, 1989) and are produced by SAA and cosmic-ray irradiation of the instrument and spacecraft.

TABLE I

GOES proton measurements.

Date/time	Flux > 10 MeV p (cm^2 s sr)$^{-1}$	>10/>30	Flux ratios >30/>50	>50/>100
20 Oct. 1989/16 UT	4×10^4	6	3	5.5
14 July 2000/13 UT	2×10^3	1.5	1.5	3
15 July 2000/09 UT	2×10^4	4	3.5	14
21 Apr. 2002/16 UT	1.4×10^2	1.6	1.9	4.9

The β-decay continuum is produced by irradiation of the germanium detectors. Long-lived background lines can be removed from the high-latitude spectrum by subtracting data taken near the equator. Residual narrow lines appear in the spectrum at high latitudes from proton irradiation of the detector and surrounding material, such as Fe and Al, that produce lines with half-lives shorter than a few minutes (Figures 3(b) and 5). The positron-electron annihilation line is the most intense line observed in both the total background and high-latitude spectra. The power law continuum is due to cosmic rays and atmospheric bremsstrahlung.

We used data accumulated on 19 April, at roughly the same geographic location as the time when the SEP-produced atmospheric gamma rays were observed on 21 April, in order to remove most of the background-line and continuum features. There is evidence for some weak residual background features from excited states of nuclei such as ^{27}Al. As there are also several sources of short-lived β^+-unstable nuclei in the spacecraft, the intense SEP-produced atmospheric annihilation line may also be contaminated by this background. RHESSI observed several atmospheric lines from excitation of ^{14}N and ^{16}O and their spallation products. Resolved line features were detected near 720, 1630, 2310, 3900, 4420, and 5115 keV. There is also evidence for many of the other lines detected by the SMM spectrometer during the intense 20 October 1989 event (100 times more intense than the 21 April 2002 event).

In Table II we compare the line energies and widths of some of the most intense lines in the atmospheric spectrum in different instruments. The lines measured by SMM and RHESSI were of the SEP irradiated atmosphere while the lines measured by HEAO 3 (Mahoney, Ling, and Jacobsen, 1981; Willett and Mahoney, 1992) were made during quiescent times and were produced by cosmic-ray irradiation. (The *Yohkoh* spectral resolution was not adequate for these line studies.) The RHESSI and HEAO 3 annihilation line energies and widths are consistent with one another in spite of the fact that the RHESSI observation may be partly contaminated by 511 keV photons from the instrument and spacecraft. Mahoney (1981) showed that the 511 keV instrumental background line was a few tenths of

TABLE II

Comparison of RHESSI, SMM, and HEAO 3 line observations.

Source	Energy, keV			Width, keV (FWHM)		
	SMM	RHESSI	HEAO 3	SMM	RHESSI	HEAO 3
e^+e^-	512.1 ± 3.0	511.3 ± 0.1	511.07 ± 0.1	–	2.44 ± 0.14	2.29 ± 0.3
^{10}B, ^{14}N	719.7 ± 3.0	723.0 ± 2.0	–	30.5 ± 8.0	21.3 ± 5.2	–
^{10}B	–	718.0	–	–	24.0 ± 8.0	–
^{14}N	–	728.0	–	–	≤15	–
^{14}N	1629.9 ± 3.0	1635.0 ± 3.0	1634.8 ± 1.4	32.0 ± 7.0	30.0 ± 6.9	20.2 ± 5.7
^{14}N	2298.0 ± 15.1	2312.5 ± 1.2	2309.4 ± 1.9	43.0 ± 10.0	25.8 ± 3.9	24.0 ± 5.4
^{14}N	3890.9 ± 20.2	3911.5 ± 8.5	–	<270	80.5 ± 13.8	–
^{11}B, ^{12}C	4435.0 ± 5.0	4422.0 ± 8.0	4428.5 ± 7.5	159.8 ± 14.0	200.0 ± 16.0	135.0 ± 12.0
^{14}N	5115.0 ± 10.1	5116.0 ± 12.0	–	152.8 ± 23.5	157.6 ± 26.5	–

TABLE III

Relative gamma-ray line fluxes from SEP impact on Earth's atmosphere.

Date/time	1.63 MeV	Relative line flux		
		2.31 MeV	4.44 MeV	0.511 MeV
20 October 1989/16 UT	0.41 ± 0.04	0.79 ± 0.09	1.00	1.29 ± 0.10
14 July 2000/13 UT	–	<0.3	1.00	1.20 ± 0.42
15 July 2000/09 UT	0.23 ± 0.03	0.48 ± 0.03	1.00	1.1 ± 0.1
21 April 2002/16 UT	0.19 ± 0.05	0.44 ± 0.06	1.00	1.8 ± 0.1

a keV broader than the atmospheric line. Within statistics, the RHESSI measured instrumental and SEP annihilation lines are consistent with each other.

The RHESSI observations appear to confirm the suggestion that two lines contribute to a feature observed near 720 keV by SMM (Share and Murphy, 2001). A single line fit to the RHESSI spectrum has a center energy (723 ± 2.0 keV) that lies between the 718 keV ^{10}B line produced in the *p,pα* reaction on ^{14}N and the 728 keV ^{14}N de-excitation line. With two lines fixed at 718 and 728 keV, we get a slightly improved fit, and find that the ^{10}B line is likely to be broader than the ^{14}N line (see Table II). The ^{10}B spallation line also appears to be about twice as intense as the ^{14}N de-excitation line, suggesting that the particle spectrum may be rather hard.

There is excellent agreement between the RHESSI and HEAO 3 line energies and widths of the strong 2313 keV line emitted in transition from the first excited state to the ground state in ^{14}N. This is true even though the line measured by HEAO 3 was produced by secondary neutrons from cosmic-ray interactions. The 1635 keV line emitted in the transition from the 3948 keV level to the first-excited state in ^{14}N, was not as well detected by RHESSI, as it is about half as strong as the 2313 keV line and lies near an instrumental artifact. This may account for the width and uncertainty being larger than that measured by HEAO 3. The energy and width of the complex at 4440 keV from the ^{11}B and ^{12}C spallation products was not as well measured by RHESSI as it was by SMM because of the weakness of the 21 April 2002 SEP event and RHESSI's lower efficiency at high energy. The measured energy of the line is about 2σ below the rest energies of ^{11}B and ^{12}C (4444 and 4439 keV). If the measured line was due to ^{11}B then we would expect to see a comparably strong line at 2124 keV from its first excited state. We searched for this line and set a 2σ limit of 8% of the 4440 keV line. This demonstrates that the measured 4440 keV line is dominated by emission from the first excited state of ^{12}C. The RHESSI measured energy for the ^{14}N line at 3890 keV is about 2σ high while the measured energy for 5105 keV line is within the statistical uncertainties.

It is possible to estimate the spectrum of SEP particles that interact in the Earth's atmosphere by comparing the relative flux in the spallation line at 4440 keV with those in the ^{14}N de-excitation lines at 1635 and 2313 keV (Share and Murphy, 2001). We list relative gamma-ray line fluxes (for an assumed incident angle of 60°) normalized to the 4440 keV line for the SEP events in Table III. The ^{14}N lines measured by RHESSI appear to be weaker relative to the 4440 keV spallation lines than those in the 20 October 1989 and roughly comparable to the 15 July 2002 measurements. Using these ratios, we have used the revised solar gamma-ray production code (Kozlovsky, Murphy, and Ramaty, 2002) to estimate the spectrum of SEP between about that interact with the atmosphere. For an assumed power-law, the SEP spectrum on 20 October 1989 has a spectral index that is steeper by ~ 0.5 than those obtained on 15 July 2000 and 21 April 2002. The softer spectrum in the October event is consistent with proton flux ratios between 10 and 50 MeV listed in Table I. The relatively high 511 keV annihilation flux observed by RHESSI may reflect this harder spectrum; however, there is also evidence that there may be a contribution from an instrumental line due to an imprecise background subtraction (The instrument response includes production of 511 keV photons produced by high-energy photons impacting the satellite).

Acknowledgements

This work was supported by NASA DPR's W-10049, W-19746, and W-19916 and by the Office of Naval Research. We wish to thank the entire RHESSI team for the success of this mission and for the tools to analyze these excellent data. We also thank Benz Kozlovsky for discussions concerning nuclear cross sections.

References

Foat, J. E. *et al.*: 1998, *Geophys. Res. Lett.* **25**, 4109.

Kozlovsky, B., Murphy, R. J., and Ramaty, R.: 2002, *Astrophys. J. Suppl.* **141**, 523.

Lampton, M., Margon, B., and Bowyer, S.: 1976, *Astrophys. J.* **208**, 177.

Letaw, J. R., Share, G. H., Kinzer, R. L., Silberberg, R., Chupp, E. L., Forrest, D. J., and Rieger, E: 1989, *J. Geophys. Res.* **94**, 1211.

Lin, R. P. *et al.*: 2000, in R. Ramaty and N. Mandzhavidze (eds.), *High Energy Solar Physics – Anticipating HESSI*, American Soc. of the Pacific Conf. Series 206, San Francisco, p. 1.

Ling, J. C.: 1973, *J. Geophys. Res.* **80**, 3241.

Mahoney, W. A., Ling, J. C., and Jacobson, A. S.: 1981, *J. Geophys. Res.* **86**, 11 098.

Share, G. H. and Murphy, R. J.: 2001, *J. Geophys. Res.* **106**, 77.

Share, G. H., Murphy, R. J., Tylka, A. J., and Schwartz, R. A.: 2001, *Solar Phys.* **204**, 43.

Smith, D. M. *et al.*: 2000, in R. Ramaty and N. Mandzhavidze (eds.), *High Energy Solar Physics–Anticipating HESSI*, American Soc. of the Pacific Conf. Series 206, San Francisco, p. 92.

Smith, D. M. *et al.*: 2002, *Solar Phys.*, this volume.

Wheaton, W. A., Ling, J. C., Mahoney, W. A., Varnell, L. S., and Jacobson, A. S.: 1989, in A. C. Rester and J. I. Trombka (eds.), *High-Energy Radiation Background in Space*, AIP Conf. Proc. 186, AIP, New York, p. 304.

Willett, J. B. and Mahoney, W. A.: 1992, *J. Geophys. Res.* **97**, 131.