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Measurements with TRACER: Discussion of Results and Future Prospects

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The individual energy spectra and relative abundances measured with TRACER, are compared with previous measurements in space and balloons, and with interpretations of air shower data. From the individual spectral slopes, we discuss constraints on models of cosmic-ray propagation through the galaxy. We also discuss the extrapolated high-energy abundances of the elements at the cosmic ray sources. The TRACER instrument is currently being refurbished for a second long duration balloon flight. The dynamic range of the measurement will then be extended to include the lighter cosmic ray nuclei, down to boron (Z = 5).

1. Introduction

The measurements of the cosmic-ray composition with TRACER [1] cover a very wide range of energies, but the present discussion will concentrate on results at the highest energies, up to 10^4 GeV/amu. Key questions are how the current measurement extends previous results, how the data constrain models of cosmic-ray propagation in the Galaxy, how compatible direct measurements are with interpretations of air-shower observations, and what can be learned about the source composition of the sources of high-energy cosmic rays.

2. Comparison with other Measurements

At energies below 40 GeV/amu, we compare TRACER results with measurements in space on HEAO-3 [2] and at higher energies with data from CRN on the space shuttle [3]. Results from the passive balloon-borne detectors JACEE [4] and RUNJOB [5] extend to higher energies than the TRACER data, albeit with very limited statistics, and only for groups of elements. Figure 1 illustrates the generally good agreement in absolute intensity between the TRACER data and the results from the space-borne detectors. As absolute intensities are plotted, without any arbitrary normalizations, but multiplied with $E^{2.5}$, this agreement indicates that systematic uncertainties are small.

An exception are the relatively rare elements S, Ar and Ca. For these, the intensities obtained from the relativistic rise of specific ionization between 10 and 400 GeV/amu tend to be higher than the HEAO data would suggest. We believe that there could be contamination in our data in this region due to insufficient charge resolution. However, this affects only these three elements, and only in the intermediate energy region. The intensities derived from the TRD measurement at the highest energies are clearly separated in charge without contamination for all elements. The highest energy results for S, Ar, and Ca are the first that have been reported for these elements. The statistical errors of the TRACER results are smaller than those of CRN, and the TRACER data extend to higher energies. Unusual features in the spectra, such as flattening or steepening are not obvious and we do not observe a steep silicon spectrum as was suggested from early data from CRN and RUNJOB.

In figure 2 the TRACER data for oxygen and iron are compared with results from the JACEE [6] and from the

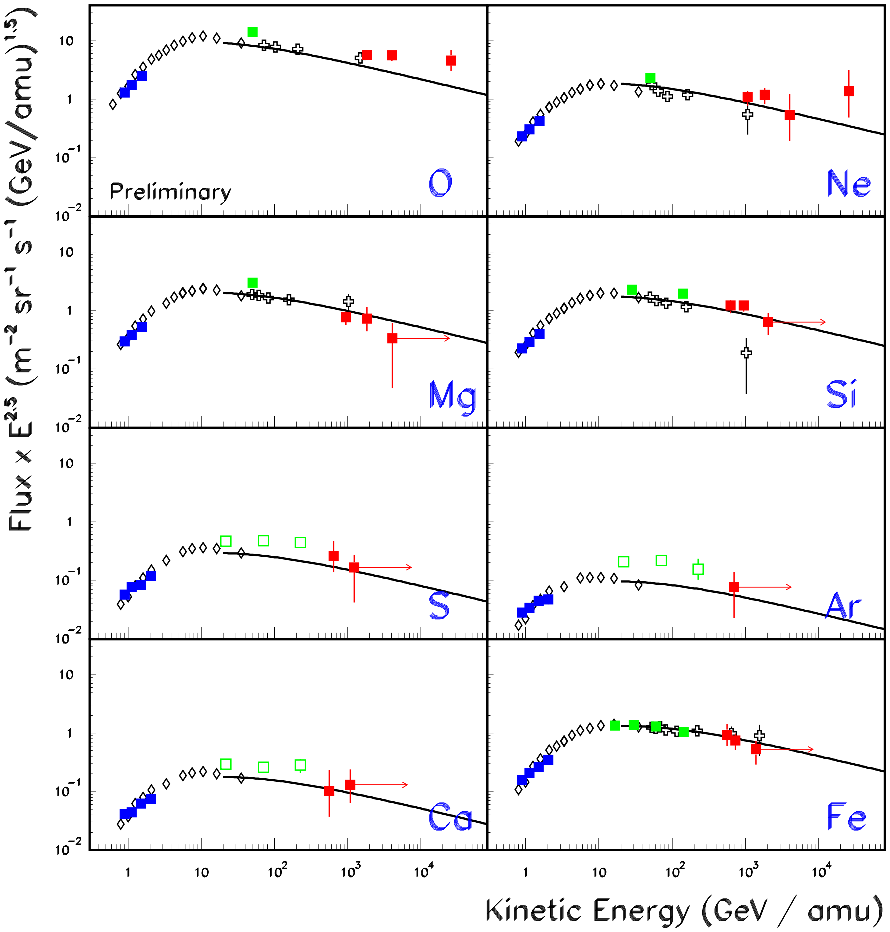

Figure 1. Differential energy spectra, multiplied by $E^{2.5}$, from TRACER (solid squares), HEAO-3 (open diamonds), and CRN (open crosses). The curves refer to predictions from a simple propagation model (see text).

RUNJOB [5] balloon flights, and with spectra derived from indirect observations of the EAS-TOP collaboration [7], and of the KASCADE group assuming different nucleus-nucleus interaction models [8]. However, these groups do not report results for individual elements: the fluxes for the "CNO group" probably have about twice the intensity than oxygen alone, while the "iron group" probably is dominated by iron. Our results do not yet overlap with the energy region of the air shower data, but the gap is becoming smaller, in particular, for oxygen. Additional measurements will indeed lead to significant constraints on the air shower interpretations.

3. Propagation in the Galaxy

The results from HEAO-3 and CRN have previously been parameterized in a simple propagation model with differential source spectra $\propto E^{-2.2}$, and an escape path length $\Lambda \propto R^{-0.6}$ for rigidities R $>$ 20 GV [9]. The spectral slope observed for a given species and energy would then result simply from the equilibrium between production in the source and loss by diffusion (diffusion coefficient $\propto E^{0.6}$) or spallation (energy-independent, but cross section increases with nuclear mass). Expected spectra according to this model are shown as curves in Figure 1. It is apparent that the new data from TRACER do not indicate a significant departure from this model.

However, it has often been argued that there might be an energy-indpendent residual pathlength Λ_0 in addition to the E$^{-0.6}$ dependence of the pathlength, i.e. $\Lambda(E) = AE^{-0.6} + \Lambda_0$. This would lead to a hardening of the energy spectra at the highest energies, as perhaps suggested in our oxygen data. A more detailed analysis of the TRACER data constrains the value of Λ_0 to $\Lambda_0 \leq 0.15 g/cm^2$.

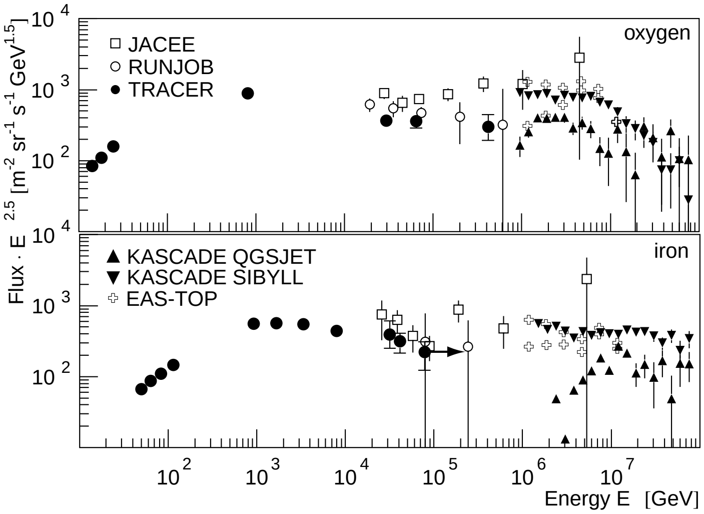

Figure 2. Energy Spectra from the balloon detectors TRACER, JACEE (as quoted in [6]), and RUNJOB, and from the interpretation of air shower data of KASCADE (for two different interaction models) and of EAS-TOP (two data points for each energy are given, representing upper and lower limits). The spectra are for oxygen and for iron for TRACER, but for the "CNO-group" and the "Fe-group" for the other observations. Note that the spectra are plotted versus total energy per particle.

4. Composition of the Cosmic-Ray Source

The elemental abundances of cosmic rays at lower energies, as compared to the solar system, favor elements with low first ionization potential (FIP), or "refractories" with high condensation temperature [10]. In the interstellar medium, the refractories are preferentially frozen out in dust [11]. Figure 3 shows the abundances of the elements at the cosmic ray source from our measurements around 100 and 1000 GeV/amu, assuming the same propagation model as illustrated in Figure 1. Compared with solar system abundances [12], the TRACER results again exhibit the familiar FIP/volatility correlation. This behavior perhaps is a little more pronounced for the CRN results, although these cover fewer elements and have inferior statistics.

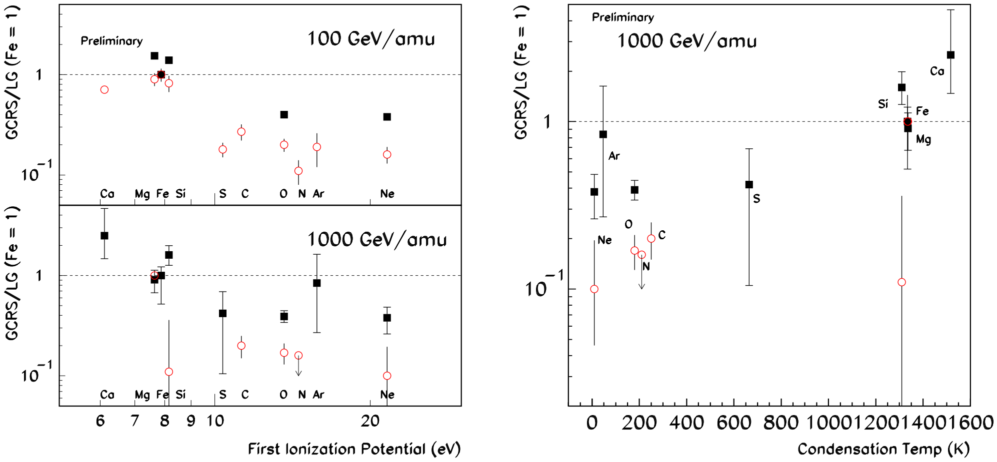

Figure 3. Abundances of the elements in the cosmic-ray source relative to local galactic abundances, plotted versus the first ionization potential (FIP), or versus the condensation temperature. Data from TRACER (squares) and CRN (open circles).

5. Future Prospects

The TRACER measurements provide significant new information on high-energy cosmic-rays, but still remain statistics limited. Additional flights of TRACER will help to improve this situation, but the TRD technique must eventually be utilized in extended space flights. The current TRACER instrument is limited in dynamic range for measurements of the elements oxygen to iron. This limitation is not intrinsic to the technique but due to the electronics used in the 2003 flight. An upgrade of the electronics, currently in progress, will extend the measurements down to boron ($Z = 5$) and hence, determine the propagation pathlength at high energies from the abundance of Boron relative to its ”parents”, mostly carbon and oxygen. Another long-duration balloon flight of the upgraded TRACER detector is planned for 2006.

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References

[1] Boyle, P.J. et al., 29th ICRC, Pune (2005) OG1.1
[2] Engelmann, J.J. et al, Astron. Astrophys, 233, 96, 1990
[3] Müller, D. et al, ApJ. 372, 356, 1991
[4] Takahashi, Y et al, Nucl. Phys. B (Proc. Suppl.) 60B, 83, 1998
[5] Furukawa, M et al, Proc. 28th ICRC Tsukuba, 1, 203, 2003
[6] Shibata, T. Nucl. Phys. B (Proc. Suppl.) 75A, 22, 1999
[7] Navarra, G. et al, 28th ICRC Tsukuba, 1, 147, 2003
[8] Antori, T. et al, Astopart. Phy., in Press 2005, astro-ph/0505413
[9] Swordy, S.P. et al, ApJ. 349, 625, 1990
[10] Meyer, J.P. et al, ApJ. 487, 182, 1997
[11] Ellison, D.C. et al, ApJ. 487, 192,1997
[12] Grevesse, N. et al, ASP Conf. Ser. 99, Cosmic Abundances, 117, 1996