29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

# What Fraction of the Kinetic Energy of Coronal Mass Ejections goes into Accelerating Solar Energetic Particles?

R.A. Mewaldt[a], C.M.S. Cohen[a], G.M. Mason[b,c,h], D. K. Haggerty[d], M. D. Looper[e], A. Vourlidas[f], M.I. Desai[b,i], J. Giacalone[g], A.W. Labrador[a], R.A. Leske[a], and J.E. Mazur[e]
*(a) California Institute of Technology, Pasadena, CA 91125 USA*
*(b) University of Maryland, College Park, MD 20742 USA*
*(c) IPST, University of Maryland, College Park, MD 20742 USA*
*(d) Johns Hopkins University/Applied Physics Laboratory, Laurel MD 20723 USA*
*(e) Aerospace Corporation, Los Angeles CA, 90009 USA*
*(f) Naval Research Laboratory, Washington DC, 20735 USA*
*(g) University of Arizona, Tucson, AZ, 85721 USA*
*(h) now at Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723 USA*
*(i) now at Southwest Research Institute, San Antonio, TX 78238 USA*
Presenter: R. A. Mewaldt (RMewaldt@srl.caltech.edu), usa-mewaldt-RA-abs2-sh13-poster

The largest solar energetic particle (SEP) events are thought to be accelerated by shocks driven by fast coronal mass ejections (CMEs). We compare measurements of the energy content of large SEP events from 1998 to 2003 to the kinetic energy of the associated CMEs to study the efficiency of this process. Using CME data from SOHO and SEP data from ACE, SAMPEX, and GOES for a total of 17 events, we find that the ratio of the SEP to CME kinetic energies ranges from ~0.1% to ~20%, with the largest SEP events giving an average SEP/CME kinetic-energy ratio of ~10%. Evidently shock acceleration is a relatively efficient process in these events. It is interesting that a similar efficiency is derived for cosmic-ray acceleration by supernova shocks.

## 1. Introduction

It is almost 30 years since the process of diffusive shock acceleration was described, and in the intervening period this process has successfully accounted for observations of several energetic particle components observed in the heliosphere, including particles accelerated by CME driven shocks, planetary bow shocks, traveling and co-rotating interplanetary shocks, the solar wind termination shock, and supernova shocks. It is therefore of interest to measure the efficiency of this ubiquitous process.

At the ACE-RHESSI-Wind workshop in October 2003, one working group had the objective of detailing the energy budget for two large solar events on 4/21/02 and 7/23/02. The first of these was a major SEP event while the second did not lead to an identified SEP event at 1 AU, possibly because it originated at solar longitude E72. One of the results of this exercise, as reported by Emslie et al. [1], was that the SEP kinetic energy in the April 21, 2002 event was a significant fraction (~15%) of the kinetic energy of the CME, suggesting rather efficient acceleration. In a study of SEP events during the Halloween, 2003 period by Mewaldt et al. [2] five additional events were added to this comparison with SEP/CME energy ratios ranging from ~1% to ~15%. In these six events protons accounted for 69% to 82% of the SEP energy, He accounted for 10% to 19%, $Z \geq 6$ ions varied from 3% to 9%, and electrons contributed ~1% to 18%. In this paper we add preliminary results for 11 additional SEP events, test some of the assumptions of the simple model used to calculate SEP energies, and comment on how the precision of these comparisons might be improved in the future.

## 2. SEP and CME Kinetic Energies

Several steps [1, 2] are involved in estimating the SEP kinetic energies: (1) Fitting spectra: The energy spectra were obtained by combining data from the ULEIS, EPAM and SIS instruments on ACE, the PET instrument on SAMPEX, and the GOES EPS sensor on GOES-8 and GOES-11 (for more information see [2]). The spectra, extending from <0.1 to >100 MeV/nuc, were fit with one of two spectral forms: the double-power-law form of Band et al. [3] or the model of Ellison and Ramaty [4]. The spectral fits were integrated from 0.01 to 1000 MeV/nuc to obtain the integrated fluences at 1 AU. (2) Correcting for particles that cross 1 AU more than once: To obtain the energy/$cm^2$ escaping from 1 AU we correct for the number of times that the average particle crosses 1 AU due to scattering on interplanetary turbulence. We use the simulation shown in Figure 1, which gives a logarithmic dependence on energy. On average, this reduces the estimated energy content of accelerated particles by a factor of ~3 to 4. (3) Correcting for longitude and latitude profiles: Studies of heavy ions >10 MeV/nuc show that the largest SEP events originate near central meridian. This is also seen in the longitude distribution of large proton events observed by GOES (see Figure 1). From these data sets we derived longitudinal e-folding longitudes of –45° for western events and –25° for eastern events. The e-folding latitude was chosen to be the average of these (-35°). Using these dependences, it is possible to integrate the total particle energy escaping through 1 AU.

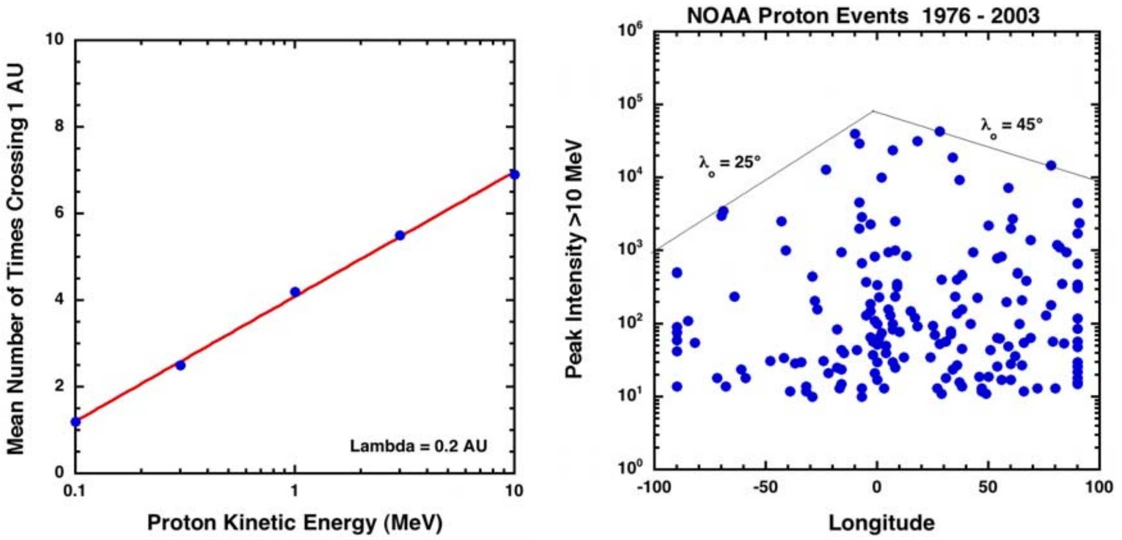


**Figure 1.** (Left) Plot of the average number of times solar protons pass outward across 1 AU as a function of energy (based on a simulation that assumed a mean free path of 0.2 AU). A logarithmic dependence was fit to these results and extrapolated to higher energy. (Right) Longitude distribution of large SEP events observed by the NOAA GOES satellites from 1976-2003. The e-folding longitudes used in this study are indicated.

In order to test whether the longitudinal profiles assumed here are reasonable, Helios 1 & 2 and IMP-8 data [5] were used to compare the estimated event fluences from three separate vantage points, as shown in Figure 2. The locations of the three spacecraft were spread over 158° in one event and 66° in the second event. The radial differences in the spacecraft locations were also corrected for by assuming that SEP fluences scale as $r^{-2}$, where r is the distance from the Sun [6]. The uncertainties on the fluence estimates were taken to be the square-root of the sum of the correction factors for longitude, latitude, and multiple crossings [2]. The agreement of the three independent estimates suggests that we have not significantly underestimated the uncertainties in this model.

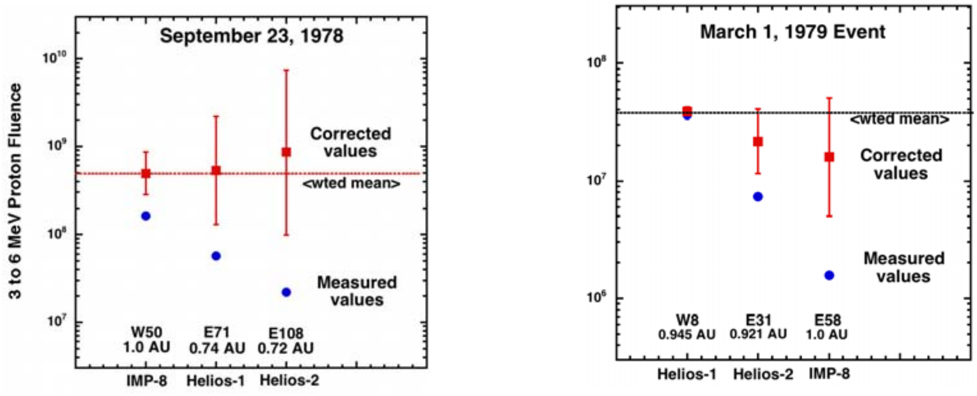


**Figure 2.** A comparison of the fluence of 3 to 6 MeV protons measured by Helios-1 & 2 and IMP-8 for the 9/23/78 and 3/1/79 events (based on measurements by Reames et al. [5]). The locations of the three spacecraft relative to the flare site are indicated. Once corrected for latitude and radius, the three estimates are in reasonable agreement.

Up to this point we have only fit the proton spectra for the 11 new events added in this paper. Based on the results from the first six events, where protons accounted for 69% to 82% of the total SEP kinetic energy, we have assumed that the protons make up 75% of the total kinetic energy. The uncertainty in the correction for other species is certainly small compared to the other uncertainties in these estimates.

The CME mass can be estimated from the total excess brightness and the velocity can be found from a fit to the radial profile [7]. We used the results of Emslie et al. [1] for the 4/21/02 event and those of Gopalswamy et al. [8] for the Halloween events. For the eleven new events we used tabulated CME masses and velocities from Gopalswamy et al. [9]. The CME masses are measured over a sector outlined by the measured angular width of the CME, its front, and the LASCO C2 or C3 occulter. Mass and energy estimates are more accurate for events on the limb than for halo CME events.

## 3. Results and Discussion

A comparison of CME and SEP kinetic energies for seventeen SEP events is shown in Figure 3. Note that the CME kinetic energies range from ~3 x $10^{31}$ ergs to ~ $10^{33}$ ergs, while the SEP kinetic energies range from ~4 x $10^{29}$ ergs to ~7 x $10^{31}$ ergs. Thus, the spread in the SEP kinetic energies is about a factor of 10 greater. It is interesting that there is a group of events where the SEP kinetic energy ranges from ~3% to 20% of the CME kinetic energy. Thus, in spite of the sizable uncertainties, it appears that shock acceleration can often transform ~10% of the CME kinetic energy into energetic particles. There are also four events where the estimated efficiency is considerably lower (less than 1%). One of these events (February 20, 2002) is commonly regarded as an impulsive event (that also had a large CME) and a second (May 6, 1998) could also be impulsive [10]. Of course, there are also CMEs for which no SEPs are observed at 1 AU. The events presented here were originally selected because the SEP intensities were sufficient for spectra to be measured, so they do not come from a representative sample of CMEs. Several considerations suggest that we may have underestimated the SEP kinetic energies. We have not yet taken into account adiabatic energy losses, which may be as large as ~50% for particles accelerated near the Sun. In some events particle acceleration continues beyond 1 AU, and only particles that scatter back inside 1 AU are counted. In addition, CME kinetic energies derived from [9] may be overestimated, since the tabulated maximum velocity was used. So, SEP/CME kinetic energy ratios may be even greater than indicated.

It is interesting that galactic cosmic rays apparently extract a similar fraction of the kinetic energy from supernova shocks in order to sustain the energy density of cosmic rays in the Galaxy over the average cosmic-ray lifetime of ~15 million years.

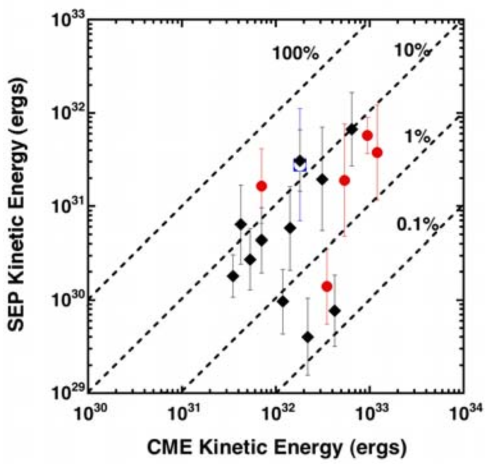


**Figure 3.** A comparison SEP and CME kinetic energies for 17 SEP events including the 21 April 2002 event (open square), the five events from October-November 2003 (circles), and 11 other events observed from 1998-2003.

## 4. Summary

These preliminary comparisons indicate that particle acceleration at CME-driven shocks can be a surprisingly efficient process; particles frequently extract ~10% or more of the CME kinetic energy. It remains to be seen why some CME-driven shocks are more efficient accelerators than others. Further comparisons with Helios and Ulysses data can improve the corrections for longitude and latitude and we are also working to improve CME energy estimates. Finally, the combination of STEREO and 1-AU data will provide multipoint in-situ data and 3-point CME images that should greatly improve these comparisons and make it possible to correlate the derived acceleration efficiency with other SEP and CME characteristics.

## 5. Acknowledgements

This work was supported by NASA under grants NNG04GB55G, NNG04088G, and NAG5-12929.

## References

[1] A.G. Emslie et al., Journal of Geophysical Research, 109, A10104, doi:10.1029/2004JA010571 (2004).
[2] R.A. Mewaldt et al., Journal of Geophysical Research, accepted (2005).
[3] D. Band et al., Astrophysical Journal, 413, 281 (1993).
[4] D.C. Ellison and R. Ramaty, Astrophysical Journal, 298, 400 (1985).
[5] D. V. Reames, L.M. Barbier, and C.K. Ng, Astrophysical Journal, 466, 473 (1996).
[6] D.V. Reames, and C.K. Ng, Astrophysical Journal, 504, 1002 (1998).
[7] A. Vourlidas, P Subramanian, K.P. Dere, and R.A. Howard, Astrophysical Journal, 534, 456 (2000).
[8] N. Gopalswamy et al., Journal of Geophysical Research, accepted (2005).
[9] N. Gopalswamy et al., Journal of Geophys. Research, 109, A12105, doi:10.1029/2004JA10602 (2004).
[10] T. T. von Rosenvinge et al., AIP Conf. Proc. #528, R.A. Mewaldt et al. eds, p. 111 (2000).