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# A simple method for solar energetic particle event dose forecasting

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**Abstract**

Bayesian, non-linear regression models or artificial neural networks are used to make predictions of dose and dose rate time profiles using calculated dose and/or dose rates soon after event onset. Both methods match a new event to similar historical events before making predictions for the new events. The currently developed Bayesian method categorizes a new event based on calculated dose rates up to 5 h (categorization window) after event onset. Categories are determined using ranges of dose rates from previously observed SEP events. These categories provide a range of predicted asymptotic dose for the new event. The model then goes on to make predictions of dose and dose rate time profiles out to 120 h beyond event onset. We know of no physical significance to our 5 h categorization window. In this paper, we focus on the efficacy of a simple method for SEP event asymptotic dose forecasting. Instead of making temporal predictions of dose and dose rate, we investigate making predictions of ranges of asymptotic dose using only dose rates at times prior to 5 h after event onset. A range of doses may provide sufficient information to make operational decisions such as taking emergency shelter or commencing/canceling extra-vehicular operations. Specifically, predicted ranges of doses that are found to be insignificant for the effect of interest would be ignored or put on a watch list while predicted ranges of greater significance would be used in the operational decision making progress.


## 1. Introduction

The onset and magnitude of solar energetic particle (SEP) events cannot yet be reliably predicted. The debate continues over correlations between SEP event onset and severity and solar observables such as coronal mass ejection (CME) shock speed and low temperature X-ray flares (Cliver and Hudson, 2002; Garcia, 2004). Forecasts with lead times of days to weeks are nonexistent. Forecasting with lead times of 2–20 h consists of observations that indicate a CME has occurred. Depending on the location of the associated activity center, particles may take as little as 30 min to reach Earth (Feynman and Ruzmaikin, 1999). Some consider CME shock prediction as the key to early warnings for astronauts and equipment alike and argue that astronauts have $\sim$12 h to seek shelter (Reames, 1999; Cohen et al., 2001). Until reliable, physical models exist, empirical, predictive models could help fill the need for an SEP event early warning system for crewed space missions. These predictive models should provide dose and dose rate time profiles as soon as possible after SEP event onset. While mitigative actions for personnel are limited, early, reliable predictions may minimize crew exposure and allow operational success.

Bayesian, non-linear regression models or artificial neural networks are used to make predictions of dose and dose rate time profiles using calculated dose and/or dose rates soon after event onset (Neal and Townsend, 2001; Hoff et al., 2003; Neal and Townsend, 2005a). Both methods match a new event to similar historical events before making predictions for the new events. The currently developed Bayesian method categorizes a new event based on calculated dose rates up to 5 h (categorization window) after event onset. Because of the current lack of measured dose data in deep space, calculated values as a function of time form the data base of dose and dose rate-time profiles used for the current Bayesian analyses. Categories are determined using ranges of dose rates from previously observed SEP events. These categories provide a range of predicted asymptotic dose for the new event. The model then goes on to make predictions of dose and dose rate time profiles out to 120 h beyond event onset using sigmoidal, non-linear growth models and Bayesian inference methods. The implementation of this methodology would utilize onboard spacecraft

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dosimetry to provide measured dose and/or dose rate values as a function of time after event onset. Local (onboard spacecraft) and remote (mission control) forecasting algorithms would provide redundant, real-time predictions of dose and dose rate time profiles. Predictions would provide information to crew members and mission controllers that would aid in operational decision making. Previous work has demonstrated that SEP event dose time profiles of all sizes may be modeled using nonlinear, sigmoidal growth functions such as Gompertz, Weibull, or Logistic functions. Furthermore, it has been shown that hierarchical models that group historical events with common characteristics provide reasonable forecasts of future dose and dose rate for new events. Historical events of all sizes can be grouped by ranges of the asymptotic dose and associated dose rates obtained early in the event. Furthermore, the selection of a given shielding configuration only changes the ranges of dose and/or dose rate values used in the hierarchical models, not the efficacy of the models used for prediction. While it is understood that particle fluxes and subsequent doses are sensitive to the monitoring location and geospatial evolution of each event, the prediction methodology is formulated to use local data at the spacecraft in order to make dose and dose rate predictions in the immediate area of the spacecraft only. Assuming all events develop as a nonlinear, sigmoidal growth function and assuming that events with similar magnitudes can be grouped together within hierarchical models, the method is insensitive to monitoring location and geospatial evolution.

We know of no physical significance to our 5 h categorization window. Rather, it seems to work well for making dose time profile predictions. Since initial publication of the Bayesian methodology, we have re-examined the categorization criteria using data from recent SEP events in 2001 and 2002 and have extended the models to include multiple-event SEP events (Neal and Townsend, 2005b). In this paper, we alter our direction slightly and focus on the efficacy of a simple method for SEP event asymptotic dose forecasting. Instead of making temporal predictions of dose and dose rate, we investigate making predictions of ranges of asymptotic dose using only dose rates at times prior to 5 h after event onset. This method would not provide an estimated finish time for an event or temporal dose rate information. This new methodology would, however, be implemented with a far simpler prediction algorithm while still providing sufficient information to make operational decisions such as taking emergency shelter or commencing/canceling extra-vehicular operations. The goal of this effort is to determine how soon after SEP event onset we can make reliable predictions of asymptotic dose ranges.

## 2. Methodology

The following sections provide an overview of our proposed model and the data used in the study.

### 2.1. Model

Previous reviews of the data (Neal and Townsend, 2001, 2005a) have indicated that the maximum value of dose rate observed early after event onset is a good indicator of event asymptotic dose. The Bayesian method for predicting dose and/or dose rate time profiles utilizes this trend to restrict the parameter spaces for the predictive models. Individual events within a multiple-event SEP event that do not accumulate their entire asymptotic dose before the arrival of a new event complicate this general trend. Currently, there is no method to predict the onset of such a new event, although ongoing efforts (Cohen et al., 2001) to utilize upstream platforms such as ACE may provide a few hours warning of an impending significant change. Instead of restricting this new methodology to predictions for single-event or the first event of multiple-event SEP events, we use our recently developed methodology for handling multiple events and "re-zero" the dose for any significant change in the dose time profile. As we are still developing criteria for defining a significant change, significant is in the eye of the forecaster. Our simple model then consists of finding the maximum calculated dose rate up to some time beyond event onset and then making a prediction of asymptotic dose using a fitted curve based on historical SEP events.

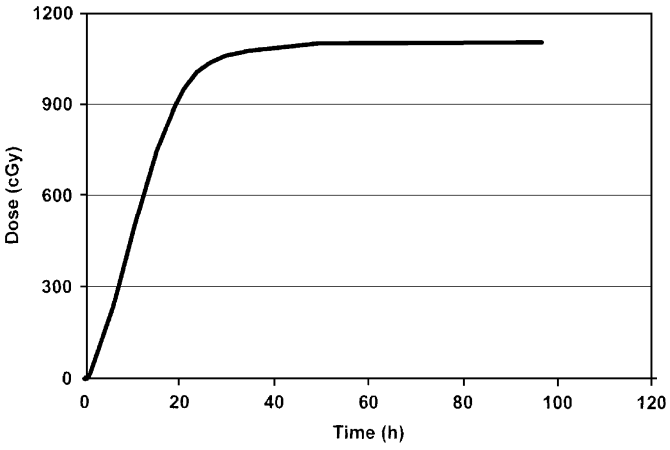


Fig. 1. November 8, 2000 SEP event dose (in water) time profile for 1 g/cm$^2$ aluminum shielding.

### 2.2. Data

Surrogate dose and dose rate data are obtained by calculation using measured proton fluxes since dose and dose rate data in deep space are unavailable for these events. Differential and integral proton flux and fluence spectra were measured on the Geostationary Operational Environmental Satellite (GOES)-7, GOES-8, and GOES-10 for the NOAA Space Environment Center (SEC) and obtained via the NOAA SEC website. Five minute average flux histories are parameterized by an exponential rigidity (momentum per unit charge) function. Parameter values are used as input to the deterministic, coupled neutron–proton space radiation computer code, BRYNTRN (Wilson et al., 1991), for transport of protons and their reaction products (protons, neutrons, H-2, H-3, He-3, and He-4) through aluminum shield material (in this case, 1 g/cm$^2$). Dose and dose rates in water are the BRYNTRN code output.

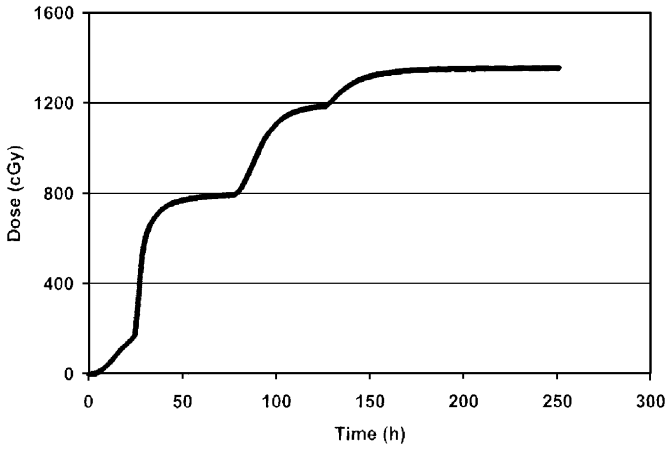


Fig. 2. October 19, 1989 SEP event dose (in water) time profile for 1 g/cm$^2$ aluminum shielding.

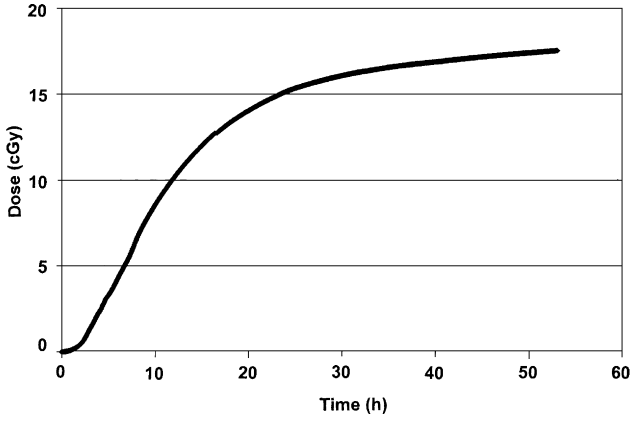


Fig. 3. April 18, 2001 SEP event dose (in water) time profile for 1 g/cm$^2$ aluminum shielding.

Because of the lack of measured dose data in deep space, these calculated values as a function of time form the data base of dose and dose rate-time profiles used for the analyses.

In order to illustrate the range of variation of dose time profiles over which the model must extend, we present Figs. 1–3. Fig. 1 shows the well-behaved, in terms of an assumed sigmoidal, non-linear growth model, single event of November 8, 2000. Fig. 2 shows the multiple events of October 19, 1989. The first of these multiple events illustrates a common occurrence for multiple-event SEP events in that events often accumulate only a portion of their asymptotic dose before the next event starts. Fig. 3 shows the event of April 18, 2001, a typical signature for small asymptotic dose events.

## 3. Results

For this study, we examined calculated dose rates for 48 events, some single and some multiple-event SEP events, listed in Table 1.

Table 1
Solar energetic particle event dates and final doses

| Event date (mm/dd/yy) | First component $D_{final}$ (cGy) | Second component $D_{final}$ (cGy) | Third component $D_{final}$ (cGy) | Fourth component $D_{final}$ (cGy) |
|---|---|---|---|---|
| 8/4/1972 | 2.1 | 1571.9 | 876 | 217 |
| 11/8/1987 | .3 | N/A | N/A | N/A |
| 8/12/1989 | 489.7 | 23.4 | 64.2 | N/A |
| 9/29/1989 | 432.8 | N/A | N/A | N/A |
| 10/19/1989 | 139 | 656 | 391 | 166 |
| 11/30/1989 | 6.06 | 53.04 | N/A | N/A |
| 3/19/1990 | 7.02 | N/A | N/A | N/A |
| 1/31/1991 | 0.34 | N/A | N/A | N/A |
| 3/23/1991 | 376.4 | 432.3 | N/A | N/A |
| 6/4/1991 | 0.53 | 49.27 | N/A | N/A |
| 8/26/1991 | 0.25 | 0.67 | N/A | N/A |
| 5/9/1992 | 0.84 | 2.92 | N/A | N/A |
| 2/20/1994 | 0.64 | 0.58 | N/A | N/A |
| 7/14/2000 | 477 | 368 | 694 | N/A |
| 11/8/2000 | 1107 | N/A | N/A | N/A |
| 11/24/2000 | 3.07 | 6.11 | 13.72 | N/A |
| 1/28/2001 | 0.72 | 0.88 | N/A | N/A |
| 3/29/2001 | 1.8 | N/A | N/A | N/A |
| 4/2/2001 | 41.6 | N/A | N/A | N/A |
| 4/10/2001 | 7.8 | 2.2 | 3.2 | N/A |
| 4/15/2001 | 54.1 | N/A | N/A | N/A |
| 4/18/2001 | 17.5 | N/A | N/A | N/A |
| 4/28/2001 | 0.022 | N/A | N/A | N/A |
| 5/7/2001 | 0.46 | N/A | N/A | N/A |
| 6/15/2001 | 0.67 | N/A | N/A | N/A |
| 8/10/2001 | 0.058 | N/A | N/A | N/A |
| 8/16/2001 | 7.7 | 22.1 | N/A | N/A |
| 9/15/2001 | 0.12 | N/A | N/A | N/A |
| 9/24/2001 | 244.5 | 258 | N/A | N/A |
| 10/1/2001 | 7.91 | 24.59 | N/A | N/A |
| 10/19/2001 | 0.28 | N/A | N/A | N/A |
| 10/22/2001 | 0.1 | 1.03 | N/A | N/A |
| 11/4/2001 | 257.3 | 134.2 | 556 | 299.5 |
| 11/19/2001 | 0.44 | N/A | N/A | N/A |
| 11/22/2001 | 155.2 | 196.8 | N/A | N/A |
| 12/26/2001 | 33.3 | N/A | N/A | N/A |
| 12/29/2001 | 0.1 | 0.74 | N/A | N/A |
| 12/30/2001 | 0.77 | 6.03 | N/A | N/A |
| 1/10/2002 | 2.88 | N/A | N/A | N/A |
| 1/15/2002 | 0.73 | N/A | N/A | N/A |
| 2/20/2002 | 0.14 | N/A | N/A | N/A |
| 3/17/2002 | 0.13 | N/A | N/A | N/A |
| 3/18/2002 | 0.41 | 0.59 | N/A | N/A |
| 3/20/2002 | 0.043 | N/A | N/A | N/A |
| 3/22/2002 | 0.22 | N/A | N/A | N/A |
| 4/17/2002 | 0.18 | N/A | N/A | N/A |
| 4/21/2002 | 244 | N/A | N/A | N/A |
| 5/22/2002 | 1.06 | 0.58 | 1.06 | N/A |

First, the maximum calculated dose rates up to 1, 2, 3, and 4 h beyond event onset were plotted, Figs. 4–7, against event asymptotic dose for single events and those portions of multiple events that reach an asymptotic dose. Events for which the asymptotic dose was not achieved were not included in Figs. 4–7 since those events should under-predict the asymptotic dose for the associated dose rate.

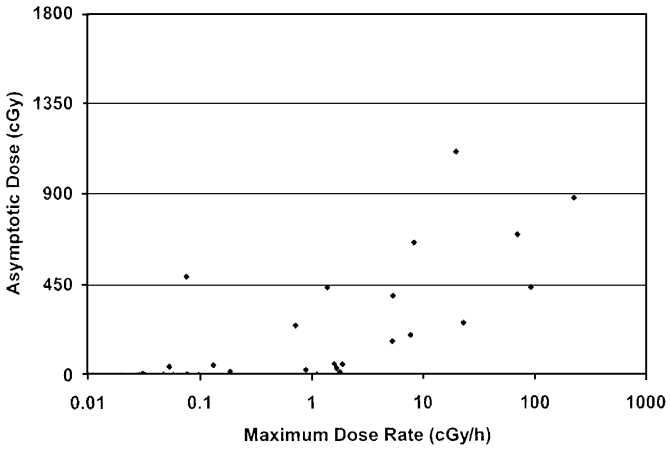


Fig. 4. Asymptotic dose versus maximum calculated dose rates up to 1 h beyond event onset for only those events in which the asymptotic dose was accumulated.

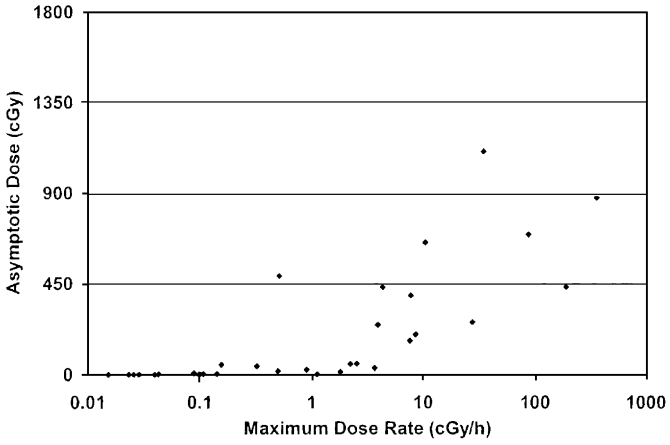


Fig. 5. Asymptotic dose versus maximum calculated dose rates up to 2 h beyond event onset for only those events in which the asymptotic dose was accumulated.

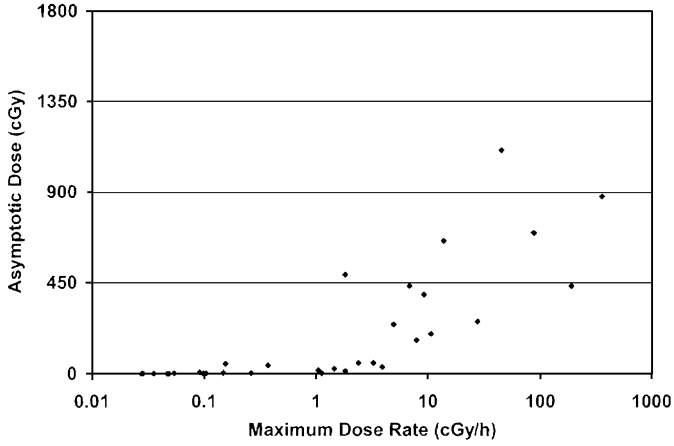


Fig. 6. Asymptotic dose versus maximum calculated dose rates up to 3 h beyond event onset for only those events in which the asymptotic dose was accumulated.

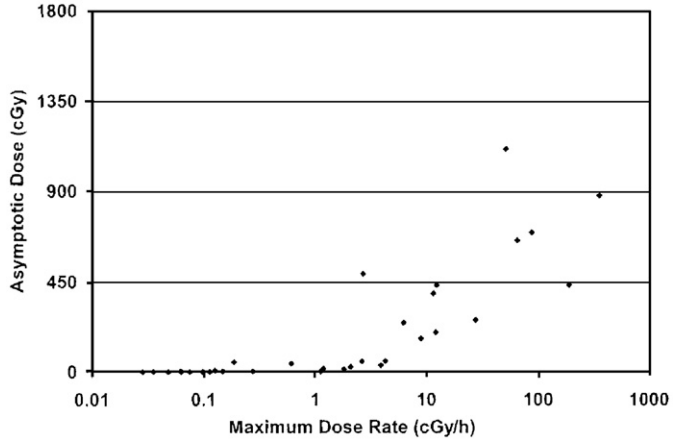


Fig. 7. Asymptotic dose versus maximum calculated dose rates up to 4 h beyond event onset for only those events in which the asymptotic dose was accumulated.

The data in each figure, for dose rates greater than 0.5 cGy/h, were fit with a single logarithmic model using Bayesian linear regression methods and the WinBUGS computer code. These fitted curves for 1, 2, 3, and 4 h beyond event onset would then serve as the "prediction curves" for new events. The prediction algorithm would actually calculate the predictive density of the asymptotic dose using Bayesian predictive methods.

As a test of this model, we calculated doses and dose rates for the October 28, 2003 multiple-event SEP event. Fig. 8 presents the associated dose time profile. We split the event into four events with start times of 0, 33, 48, and 126 h, again, based on forecaster judgment.

For each of these four events, we determined the maximum dose rate up to 4 h beyond event onset and used these values as input for the Bayesian predictive model. Table 2 provides the posterior density mean value and associated probability intervals for each of the four events at 1, 2, 3, and 4 h beyond event onset.

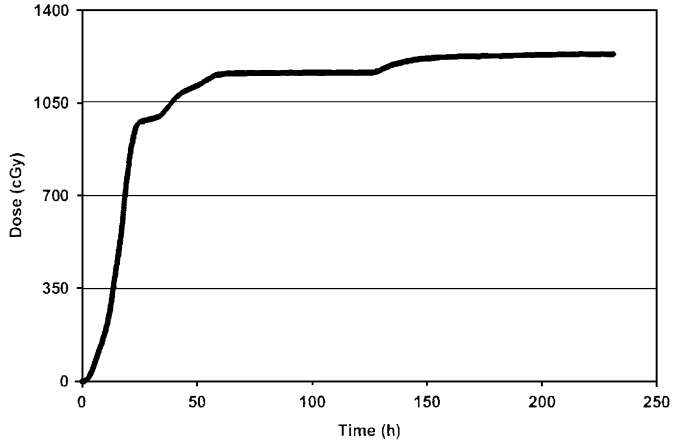


Fig. 8. October 28, 2003 SEP event dose (in water) time profile for 1 g/cm$^2$ aluminum shielding.

Table 2
Predicted posterior density mean values and associated probability intervals for the October 28, 2003 event

| Event number and calculated final dose (cGy) | Hour 1 prediction and 95% probability interval (cGy) | Hour 2 prediction and 95% probability interval (cGy) | Hour 3 prediction and 95% probability interval (cGy) | Hour 4 prediction and 95% probability interval (cGy) |
|---|---|---|---|---|
| 1/998 | 169/0–701 | 286/0–775 | 370/0–848 | 411/0–840 |
| 2/109 | 298/0–822 | 371/0–856 | 378/0–853 | 353/0–778 |
| 3/55 | 300/0–824 | 235/0–722 | 239/0–714 | 240/0–665 |
| 4/68 | 157/0–691 | 101/0–600 | 146/0–629 | 199/0–627 |

## 4. Discussion

Two general trends can be seen in Figs. 4–7. First, there appears to be a "threshold" dose rate, below which, the dose is insignificant for almost any application. This threshold appears to remain fairly constant at a dose rate of approximately 0.5 cGy/h. There is a single outlier point at approximately 490 cGy from the August 12, 1989 multiple-event SEP event at both 1 and 2 h beyond event onset. The second general trend is a logarithmic trend of asymptotic dose versus dose rate beyond 0.5 cGy/h. These two trends form the basis of our simple methodology for the prediction of asymptotic dose given observed dose rates early after event onset: (1) below the threshold value of dose rate, the event would be put on watch with operators and mission controllers looking for significant changes in the dose time profile that would require a re-zeroing of the profile and subsequent checking of the dose rate after the new event onset and (2) above the threshold value of dose rate, the new dose rate value would be used as input to the Bayesian predictive model, thus providing a predicted asymptotic dose value and its associated uncertainty.

The predictions for the October 28, 2003 event were poor. The second of the four events did not reach its asymptotic dose thus leading to an over-prediction of its final dose before the beginning of the third event. Because the prediction curves are based on a single, simple logarithmic model, predictions of new events will tend towards the average of historical values. In the case of the October 28, 2003 event this leads to significant under-prediction for the first event and significant over-prediction for the second, third, and fourth events. Additional events will need to be examined to determine the overall effectiveness of this methodology.

We are also investigating an interesting multiple-curve model using the data from this study in which 2 or 3 logarithmic curves are used to fit the data. Fig. 9 shows the data from Figs. 4 with three fitted curves. Unfortunately, one must have at least one more piece of information to decide which curve to use for the prediction.

We see a parallel with this multiple-curve model in the current Bayesian hierarchical, non-linear regression models for predicting dose time profiles which use the general trend of asymptotic dose versus dose rate to group similar historical events by dose rate early after event onset. It is the nature of a hierarchical model to group similar objects within a population but to allow individuals to pursue their own projection within the parameter space defined by the population. This helps to explain the failings of previous non-hierarchical models which tended to under-predict the asymptotic dose but gradually predicted more accurate asymptotic doses as time progressed.

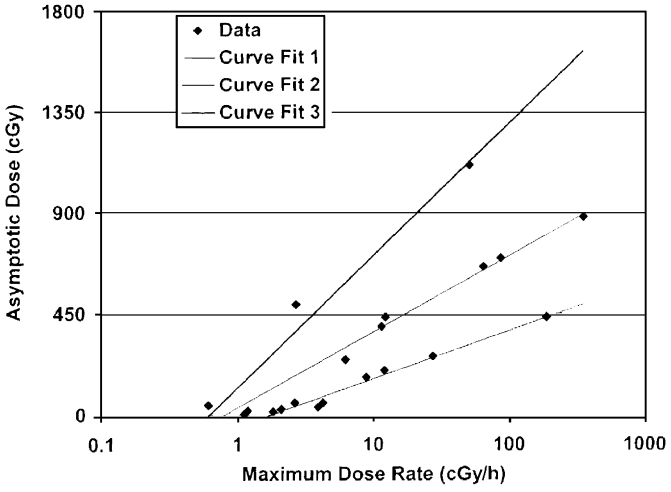


Fig. 9. Multiple-curve model linear regression fits and maximum calculated dose rates up to 4 h beyond event onset for only those events in which the asymptotic dose was accumulated.

## 5. Summary

A new, simple method has been developed for making predictions of asymptotic dose using calculated dose rates at 1, 2, 3, and 4 h beyond SEP event onset. The method fits historical data at each hour beyond onset with a single logarithmic curve using Bayesian inference models. While this work only considered a shielding configuration of 1 g/cm$^2$ of aluminum, previous work has shown that the selection of a given shielding configuration only changes the ranges of dose and/or dose rate values used in the hierarchical models, not the efficacy of the models used for prediction. As such, we do not believe that this simple methodology is limited to the assumed shielding configuration. This method would not provide an estimated finish time for an event or temporal dose rate information. This new methodology would, however, be implemented with a far simpler prediction algorithm while still providing sufficient information to make operational decisions such as taking emergency shelter or commencing/canceling extra-vehicular operations.

It should be noted that this method is limited in its support of operational decisions in the case of an on-going EVA since a decision to terminate the EVA would need to be made on the order of 1 h after SEP event onset. Predictions of asymptotic dose were made for the four separate events that made up the October 28, 2003 event. Predictions were generally poor and, due to the nature of the assumed model, tended towards historical average values. Additional events must be examined to determine the ability of the model to generally make reliable predictions of asymptotic dose early after event onset. Interesting parallels with current Bayesian hierarchical, non-linear regression models for predicting dose time profiles were discovered when the single logarithmic models were extended to multiple-curve models. This helps to explain the failings of previous non-hierarchical models which tended to underpredict the asymptotic dose but gradually predicted more accurate asymptotic doses as time progressed. Revisions to the hierarchical, non-linear regression models will be investigated in the future as a result of these findings.

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