# Chapter III
# Computational method

## Analysis of Data from Spacecraft

The data in this thesis are from flares at the Sun that are observed by four spacecraft instruments. The data include total rates of protons and electrons from eight directional "sectors" as the spacecraft rotates in the ecliptic plane (the plane of the Earth's orbit around the Sun), i.e., eight intervals of $45^o$ each. Furthermore, for a limited number of particles, a full set of pulse height(PH), or signals, from each detector is transmitted to Earth. From the pulse height data, we can determine the energy of individual particles.

The impulsive flare of July 20,1981 and the gradual flare of January 2,1982 are from U. of Chicago instrument on board the International Sun-Earth Explorer-3/International Cometary Explorer (ISEE-3/ICE) spacecraft, which was stationed near the inner Lagrangian point between the Earth and the Sun (where the forces toward the two bodies are balanced). The initial data processing yields magnetics tapes containing all data from the instrument. The program (Ruffolo 1995) was developed to extract particular data of interest for individual protons (see Figure 3.1): the time of detection, sector, energy, and "live time ratio," or the number of particles in space for each particle in the pulse height data. The particles we consider in this study are protons with energy bins from E1 to E5 as 27-39, 39-55, 55-75, 75-105, and 105-147 MeV respectively.

The data of the flare September 23,1978 are from three spacecraft: ULEWAT instrument on board ISEE-3/ICE, HELIOS I, and HELIOS II. The data

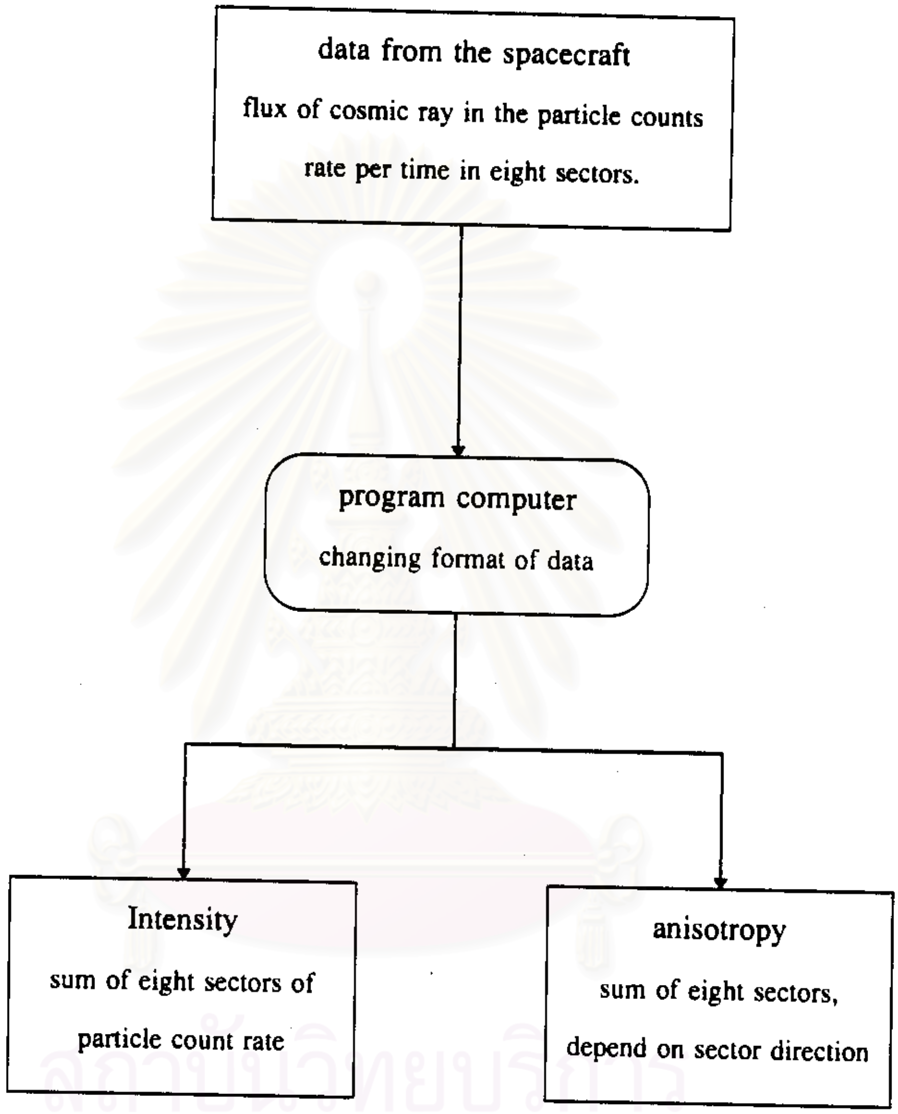


Figure 3.1: The chart of method to extract data from the spacecraft.

of this flare received from Dröge by E-mail. The data from ULEWAT are in the form of fluxes of electrons (counts per sec) with energies from E1 to E4 as 0.18, 0.25, 0.61, and 1.10 MeV respectively. The data from the two HELIOS spacecraft are similar to those from ULEWAT, but are different in the energies from E1 to E4 as 0.8, 2.2, 4.5, and 6.3 MeV respectively.

## Simulations and Variable Mean Free Path

In fits to simulations (Ruffolo 1995), we are not able to accurately measure the parameter $b$, defined by $k_r \propto r^b$ ($k_r \approx 10^{21}$ to $10^{22}$ cm$^2$/s). The value of $b$ has very little effect on the observed flux of solar cosmic rays at 1 AU, especially if one simultaneously adjusts the value of $\lambda$. Therefore, if $b$ is a free parameter, it will not be well constrained by data from a single spacecraft, and the uncertainty in $\lambda$ will increase. Thus it would seem best to simply choose one form for the variation of $\lambda$ with $r$ (one value of $b$) and to find the magnitude of $\lambda$ that best fits the data.

The transport equation (Ruffolo 1995) that we used in the transport simulation is very complex from many parts of the equation: streaming, convection, focusing, differential convection, scattering, and deceleration. This is the transport equation:

$$
\begin{aligned}
\frac{\partial F(t,\mu,z,p)}{\partial t} &= -\frac{\partial}{\partial z}\mu v F(t,\mu,z,p) && \text{(streaming)} \\
&- \frac{\partial}{\partial z}\left(1-\mu^2\frac{v^2}{c^2}\right) v_{sw} \sec\psi F(t,\mu,z,p) && \text{(convection)} \\
&- \frac{\partial}{\partial \mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{sw}}{v}\sec\psi-\mu\frac{v_{sw}v}{c^2}\sec\psi\right] \\
&\cdot(1-\mu^2)F(t,\mu,z,p) && \text{(focusing)} \\
&+ \frac{\partial}{\partial \mu}v_{sw}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2) \\
&\cdot F(t,\mu,z,p) && \text{(differential convection)} \\
&+ \frac{\partial}{\partial \mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial \mu}\left(1-\mu\frac{v_{sw}v}{c^2}\sec\psi\right)F(t,\mu,z,p) && \text{(scattering)} \\
&+ \frac{\partial}{\partial p}p v_{sw}\left[\frac{\sec\psi}{2L(z)}(1-\mu^2)+\cos\psi\frac{d}{dr}\sec\psi\mu^2\right] \\
&\cdot F(t,\mu,z,p). && \text{(deceleration)}
\end{aligned}
$$

Simulations of the cosmic ray transport are on UNIX computers because of the large memory required. To run the simulation, we have to input many variables about the time of flare occurring, position of the spacecraft, etc. This is the example of the simulation input parameters in the flare data sheet (see appendix III) for the flare September 23, 1978 from ULEWAT spacecraft.

Flare date (year month day): *1978/09/23*

Day of year (DOY): *266*

H$\alpha$ data: *0940* UT at *+35* ° (+N,-S) and *50* ° (+W,-E)

Solar wind condition: *nearly constant speed, density*

Solar wind speed: *370* km/s

$\beta_{sw} = v_{sw}/299{,}790$ km/s = *0.001234*

Latitude of magnetic field: *22.5* ° (+N,-S)

Longitude of magnetic field: *110* ° (+N,-S)

$r_{s/c}$ = *0.98972* AU

Solar latitude of Earth = *+7* ° (+N,-S)

Solar latitude of spacecraft = *+7* ° (+N,-S)

Cosmic ray particle species: *electron*

Mass (Mev/c$^2$): *0.511*

The other important input parameter is $\lambda$. By varying $\lambda$, the simulations yield many results. We try many $\lambda$ because we want to know what $\lambda$ is suitable for the flares we studied.

**1. The flare of 1981 July 20** The anisotropy data exhibit abrupt changes that can not be explained with a simple model of cosmic ray transport from the Sun. We propose that such changes are due to the rapid fluctuations in the magnetic field at that time, and generalize that it may be difficult to model the anisotropy whenever the field is highly variable. So we studied the intensity of this flare. We studied the intensity for various energies by separately extracting data and performing simulations for each energy of particles from E1 to E5, and merging E4 and E5 into one because the low of intensity. The $\lambda$ was varied for simulations from 0.08 AU to 0.25 AU. Furthermore, we studied the intensity data without energy separation for comparing the result with the flare 1982 January 2. The $\lambda$ was varied from 0.08 AU to 0.45 AU.

**2. The flare of 1982 January 2** This time the interplanetary magnetic field was steady, and both the intensity and anisotropy×intensity vs. time could be fit simultaneously, allowing a determination of both the scattering mean free path and the injection profile. The simulation for this flare, $\lambda$ was varied for simulations from 0.05 AU to 0.45 AU.

**3. The flare of 1978 September 23 (Data from ULEWAT)** In this flare, we received only the electron intensity data from Dröge. We separated energy spectrum data into 4 levels of energy. The $\lambda$ was varied for simulations from 0.05 AU to 0.25 AU.

**4. The flare of 1978 September 23 (Data from HELIOS I and HELIOS II)** The simulations is the same as ULEWAT but different in the energies, and the input parameters. The spacecraft are different so the location input parameter of these spacecraft are different too.

We have to change parameters in the flare data sheets before running simulations for each flare according to the parameter (spacecraft position, solar wind speed, magnetic field line condition, etc.).



## Fitting Procedure for Determining the Duration of Emission

We have developed a general, quantitative fitting technique for determining the injection profile of cosmic ray particles from the Sun. The detectors

| λ | flares | | | | | |
|---|---|---|---|---|---|---|
| (AU) | '81 ph | '81 pr | '82 ph | '78 Ulewat | '78 Helios I | '78 Helios II |
| 0.05 | x | | | x | x | x |
| 0.08 | x | x | | x | x | x |
| 0.10 | x | x | | x | x | x |
| 0.12 | x | x | | x | x | x |
| 0.15 | x | x | x | x | x | x |
| 0.20 | x | x | x | x | x | x |
| 0.25 | x | x | x | | x | x |
| 0.30 | | | | x | | |
| 0.35 | | | x | | | |
| 0.45 | | x | x | | | |

Table 3.1: The mean free path (λ) for simulations.

measure the intensity vs. time near the Earth(for ISEE-3). So far, we have used the former data to determine the injection profile for many flares.

This is an example of an inversion problem: we have data on the "output" of the interplanetary transport (the cosmic ray intensity near Earth), and we know the "response function", which gives the output assuming the injection takes place a single instant in time. From these, we can in principle determine the true injection function, the injection of particles from the Sun into the interplanetary medium as a function of time. However, in practice this procedure can be quite difficult (see Figure 3.2).

Last year, the quantitative fitting technique is the least squares technique express the injection as a piecewise linear function of time. To do that, a routine "makeff" calculated the response function due to a "triangular" injection function, starting from no injection at the start time, rising linearly to a peak injection of 1 at the peak time, and declining linearly to 0 at the end time. The impulsive flare of 1981 July 20 and the gradual flare of 1982 January 2 were used by this method. It yielded the good result of mean free path and injection function, but

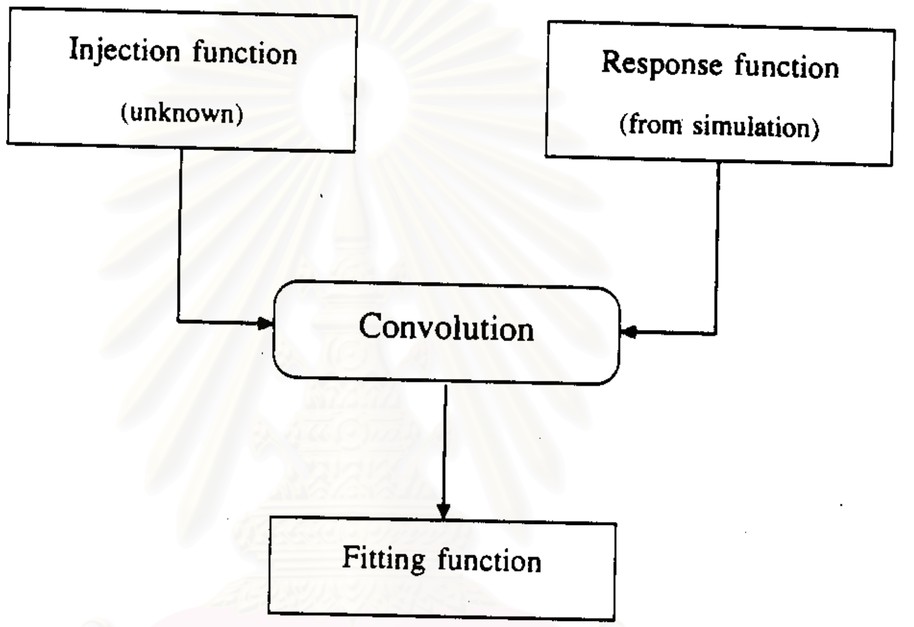


Figure 3.2: The chart of convolution for fitting function.

this procedure used the human measured by defining begin time, peak time and end time, and determining the best fit from the picture in monitor. So the new method for determining the injection function is introduced. It is the conjugate direction optimization method (Appendix 3). This method automatic finds the best injection function. To find the injection function, we assume the functional form is $f = [C/(t - t_o)]e^{-A/(t-t_o)-(t-t_o)/B}$, where A and B are the variables and $t_0$ is the one variable of the flare beginning time. This function comes from the two dimensional propagation at the Sun's surface. By this method we receive the best-fit variable $A$, $B$ and $t_o$. This procedure to find the three variable is used the statistical technique fit the data with a model. One can quantitatively determine the set of coefficients of each function that minimizes $\chi^2 = \sum_i (y_i - \hat{y}_i)^2/\delta_i^2$, the sum of the squared ratio between the duration between the data, $y_i$, and the model, $\hat{y}_i$, and the uncertainty, $\delta_i$, of the data at each point $i$. Thus we have a truly quantitative measurement of the injection function, complete with uncertainties that arise from the uncertainties in the data. This procedure (see Figure 3.3) begin at the injection function, by assuming the value of three variables, $A$, $B$, and $t_0$ for the injection function, and then convolute the result with response function from the simulation. We will receive the fitting function which the its structure is the same as data from the spacecraft after extracting. Chi-square is the result of statistical comparison for the two types of data. The conjugate direction optimization will check chi-square, if it is the least we will get the best $A$, $B$, and $t_0$ for the $\lambda$ in response function. If not, the new $A$, $B$, and $t_0$ will send to the injection function and start the loop again.

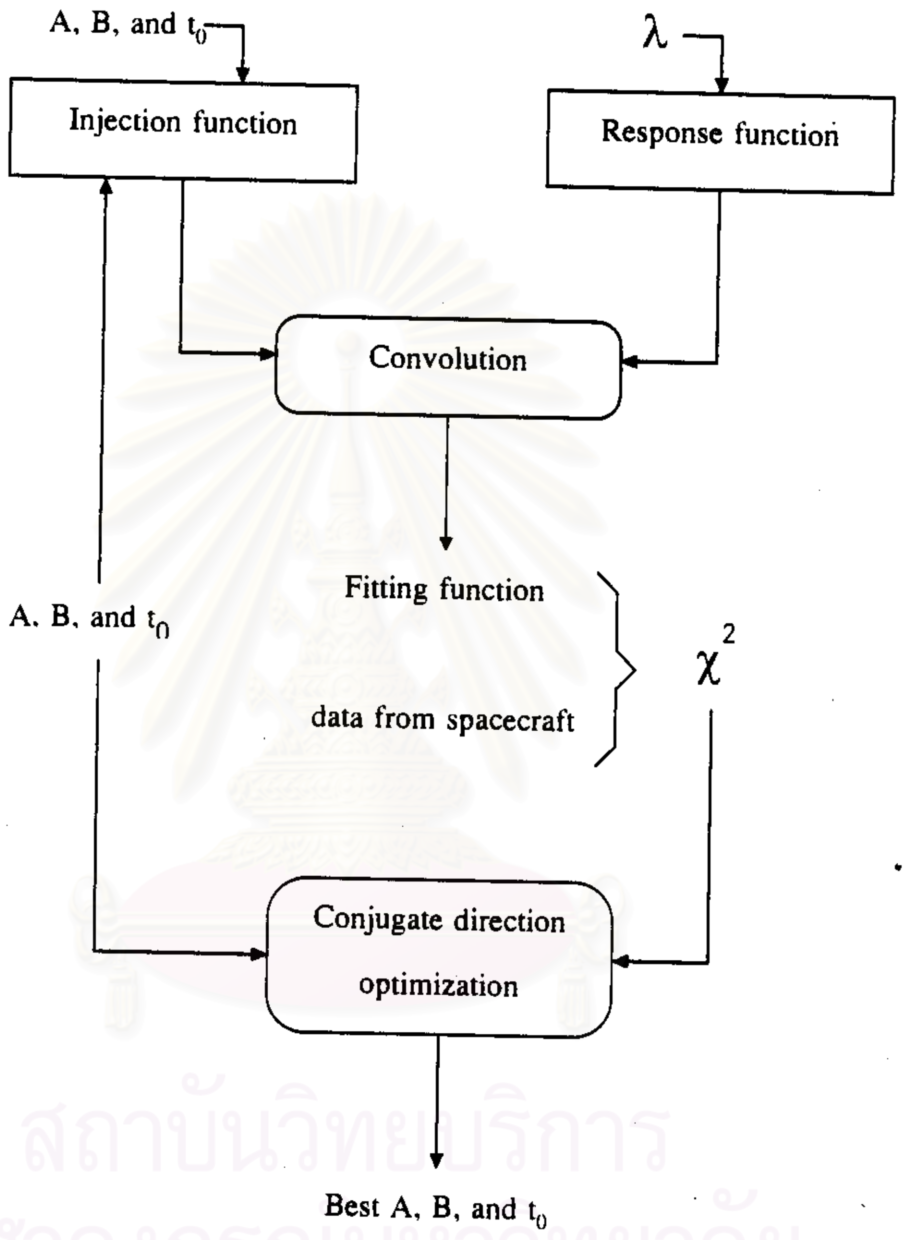


Figure 3.3: The chart to make the best fit.