Proton Flux Prediction Model at Earth Environment to E > 10 MEV

Eduardo del Pozo García, Jorge Valiente Márquez, Isabel Tatiana Rodríguez Esnard

Instituto de Geofisica y Astronomia Calle 212 #2906 e/ 29 y 31 La Coronela, La Lisa 11600, C. Habana, Cuba. Pozo@iga.cu, valiente@iga.cu, tatiana@iga.cu

Key Words: Proton Flux, Prediction, CME, SW, SPE, Heliolongitude

Abstract: One improvement of the 1989 proton flux intensity prediction model is presented with the inclusion of new input variables: The parameters of the Solar Wind, like an approximation of the state of the interplanetary media by which propagate and interactuate the coronal mass ejection as well as the proton flux emitted.

87 proton events were analyzed and identified with the flares in the visible disk of the Sun. They have the proton flux maximum intensity with energy: E>10 MeV, and with intensity J10 > 1-5 cm-2 s-1 sr -1 at the Earth environment.

Using the multiple regression method by steps with variance analysis, the relationships of the proton flux intensity were obtained with:

- The radioemissión maximum intensity of the solar event at the frequencies of 7 Ghz, 9 Ghz and 15 GHz,
- The heliolongitude "θ", for the whole Sun visible hemisphere θ Є[-90,90],
- The quotients of the radioemissión intensities like radiospectra parameters,
- The density and speed of the Solar Wind, as well as the values of
- The Solar Wind magnetic field ecliptic components and their modules.

The obtained approximations for the proton flux intensity is better than that of the 1989 model, by the biggest value in the obtained correlation coefficient (0.87-0.97), and also by the 30 - 50% smaller value of the standard error of the adjustments, in relation to the adjustments without the new parameters.

INTRODUCTION

For the solar proton flux intensity characterization several relationships have been established:

- Initial works [Akinjian, 1977][Chertok;1982], they were studied the main regularities that characterize the link between proton flux parameters arriving to the Earth after having occurred a flare at the Sun and the parameters of the corresponding burst. In this case, in quality of burst initial parameters in was used the frequencies of 3, 9, and 15 Ghz.
- Later a great additional material was analyzed of the proton events and burst occurred in the years 1980-1986. And in 1987 some quantitative prediction algorithms of the intensity and the proton flux energy spectral index at the Earth neighborhood were obtained [Fomichev V.V., Chertok I.M., Del Pozo, E., 1989,---1989b].
- Next an ulterior development of the algorithms was made and was obtained the proton flux intensity directivity diagrams in the ecliptic plane near the [Del Pozo, E.; Valiente J.F. ;1996,---1998,---1998 b].
- In 1998 - 2000 the effect of the interplanetary media state in the proton flux intensity was determined, that allowed to consider the inclusion of the solar wind parameters as input data to improve the quantitative prediction quality [Del Pozo, E. , 2000].

Following the general conception of the model developed in 1998 (fig1) [Fomichev, et al1989] [Del Pozo, E. 1998], the intensity of the proton flux at Earth Environment can be calculated by:

Ji = K(SF1/SF2)Ji (SF??) for i = 1,2,3; according to the intensity level in metric band

Ji - proton flux maximum intensity the near the Earth

SF- maximum radioemission at the frequency F at centimetric band
θ - flare heliolongitude
K(SF1/SF2) - correction factor from the radioespectral parameter SF1/SF2

With posteriority to the conformation of the initial model (fig.1), were obtained the relationships for the proton flux directivity [del Pozo et al 1996,--- et. al 1998], but they are different to the previous ones [Fomichev, et al1989], they are valid for the whole visible hemisphere of the Sun [90,90], that is to say a single relationship for each radioemission frequency whose intensity is used for the calculation of the proton flux intensity. In them an approximately quadratic dependence of the logarithm of the proton flux intensity with the heliolongitude was obtained. This allowed to obtain the East-West asymmetry with respect to the central meridian in the case of the intense metric component proton events (fig.2).

Nevertheless, the first model general conception (fig.1) include the characteristics of the propagation of the proton flux through the flare heliolongitude parameter, as an approximation of the proton event position at Sun. This approximation has some information on the solar proton propagation through the interplanetary media according to the relative position between the Earth and the solar event, which characterizes in general form the propagation through the magnetic line spiral structure of the interplanetary media. However, this first model conception does not consider the different interplanetary media states.

A first analysis of the solar wind parameters [del Pozo; 2000, ---2000a] allowed to know the existence of a relationship between the intensity of the proton flux not explained by the model (fig.1), with the density and the speed of the solar wind for the soft metric component proton events (fig.2). These dispersion graphics show positive correlation with the solar wind density and, negative correlation with the solar wind speed.

That is to say to greater solar wind density when the media is more dense and, when the solar wind speed is low, and greater is the difference between this speed and the CME ejected plasma speed the greater proton flux intensity takes place.

Present paper improves the proton prediction model including as input variables for the calculation some of the solar wind parameters.

Materials and Methods.

A database was made on WINDOW with the EXCEL software. The selection of the events was made by the analysis of the proton events associated to CME that are identified with the flares in the visible disk of the Sun.

They were considered as proton events those that present a proton flux maximum intensity observed at the Earth with intensity I10>1- 5 cm-2 s-1 sr –1 and energy E > 10 MeV. They were also included the solar events that satisfied the proton criteria of “Solar Geophysical Data” [1966- 2001], and the solar wind parameters values of the events were included.

The complex proton events that are observed on the background of a strong geomagnetic perturbation that causes a complementary variation of the parameters of these proton fluxes were not included in the analysis [Fomichev et al1989].

Then, 87 solar events were selected, 41 of soft metric radioemission (less than 5000 UF), and 46 of intense metric radioemission (equal or greater than 5000 UF).

The database this constituted by 19 variables, and for each event it gives information on:

- The burst radioemission associated to the CME
- The position of the flare associated to the CME
- The state of the interplanetary media before the burst radioemission takes place
- The proton flux intensity maximum with energy E > 10 MeV that later arrived to the Earth neighborhood

As approximation to the interplanetary media state the solar wind parameters values of the hourly mensuration previous to the centimetric burst maximum associated to the proton events were included. They are: density, speed, temperature, and magnetic field components For the analysis stepwise multiple regression method was applied to determine the relationships of dependence of the proton flux intensity observed at Earth neighbourhood with the input variables:

- The radioemission maximum intensity in centimetric band (S_F) at 6700 Mhz (S7), 9500 Mhz (S9) and 15000 MHZ (S15)
- The powers of the heliolongitud θ, θ^2, θ^3, θ^4
- The S7/S9, S7/S15 and S9/S15 parameters are the quotients of the burst maximum intensities at 6700, 9500 and 15000 Mhz , which characterize the radioespectrum
- The solar wind density (Den) and the solar wind speed (Vel)
- The three BGSE components of the solar wind magnetic field (B_j) and their modules (abs B_j)

Proton Flux Prediction Model to energies E > 10 MeV at the Earth Environment

The new general conception of the model is illustrated at the figure 4, which includes the different interaction degree with the interplanetary media. From here the necessity to analyze the proton events with some solar wind parameters that characterize the state of the interplanetary media before taking place the CME at the Sun.

The general relation based on the new model conception with the former mentioned input variables is:

$Ji = Ji (S_F, \theta, \theta^2, \theta^3, \theta^4_., S_{F1}/S_{F2}, Den, Vel, B_j, absB_j)$

Here i= 1, 2 intense or soft metric radioemission and
j= 1, 2, 3 the magnetic field BGSE components

The characterization of the proton flux has been carried out on the following conceptual base:

- To reach enough energy, to leave the Sun and its neighborhood at relativistic speeds the protons should be strongly accelerated during some time, jointly with the electrons in the high energetic plasma.
- The accelerated electrons emit intensely in radio waves giving place to the type II bursts associated to the shock wave, being the radioemission intensity in centimetric band an indicator of the acceleration degree reached by the particles.
- According to the magnetic field intensity and its topology in the area is the interaction degree at high corona, which determines the conditions of propagation both of the shock wave and the high energy charged particles. The particles go leaving the ascending perturbation as it moves for the high corona, being the radioemission in metric band an

indicator of the level of this interaction, and its intensity characterizes two basic types of proton event behavior, the intense metric component events and those of soft component.

- The accelerated particles and the shock wave propagate toward the exterior of the Sun going to the interplanetary media. While they advance for the interplanetary media, they propagation are modified by some factors which depends of the interplanetary media state:

    - The interplanetary media state is characterized in the first place by the spiral structure of the interplanetary magnetic field. This structure changes the particles propagation direction, in such a way that observing from the Earth they are deviated toward the East of the Sun
    - The degree of spiral lines curvature of the interplanetary magnetic field changes and is related with the solar wind speed [Reinier et at 1995]. This changes modifies the spiral lines effect on the proton propagation and, it modifies the values of the intensity of the proton flux at the Earth neighborhood.
    - The shock wave interactuate with the interplanetary plasma, the interaction is greater in the event cases of soft metric radioemission component and, changes the proton flux intensity. The intensity increases when the interplanetary plasma is slow and dense [Del Pozo et al 2000].

Therefore the intensity of the proton flux that arrives to the Earth depends on the values of those parameters that contain information on the previously mentioned processes:

- The intensity of radioemission at centimetric band, associated to the triggering area of the processes of acceleration. It is an indicator of the initial magnitude of the particles acceleration which originates the SEP (Solar Energetic Protons)
- The radioemission intensity at metric band as an indicator of the output conditions and the perturbation propagation at high corona.
- The relative position between the proton emission area at the Sun and the position of the Earth in its orbit, fundamentally characterized by the heliolongitude of the emitting area, to this factor the flare heliolongitude is an approximation.
- The parameters of the solar wind as indicators of the interaction degree in the interplanetary media

Obtained Relations:

Six groups of relationships were obtained that they are presented in two squares:

- The first three groups in the first square for intense metric component events and
- The following three groups in the second square for soft metric component events

Intense Metric Radioemission Component Events

1. Without including the solar wind parameters, 46 cases. Proton flux relations with:

- La radioemission en banda centimétrica (S7, S9, S15)
- La heliolongitude “θ”

$$LogI7 = 1.37(LogS7) + 0.022\theta - 1.91 * 10^{-4}\theta^{2} - 3.33$$

$$LogI9 = 1.30(LogS9) + 0.021\theta - 1.94 * 10^{4}\theta^{2} - 3.18$$

$$LogI15 = 1.13(LogS15) + 0.020\theta - 2.02 * 10^{-4}\theta^{2} - 2.48$$

Correlation	E.Std
0.80	0.84
0.80	0.85
0.80	0.85

2. All cases 46. Proton flux relations with:

- the radioemission in centimetric band (S7, S9, S15, S7/S9)
- the heliolongitude “θ”
- solar wind density (Den)

$$LogI7 = 1.35(LogS7) + 0.021\theta - 1.86 * 10^{-4}\theta^{2} + 0.068Den - 3.81$$

$$LogI9 = 1.30(LogS9) + 0.021\theta - 1.86 * 10^{-4}\theta^{2} + 0.068Den - 3.72$$

$$LogI15 = 1.10(LogS15) + 0.020\theta - 1.91 * 10^{-4}\theta^{2} + 0.068Den - 2.95$$

Correlation	E.Std
0.88	0.67
0.88	0.69
0.87	0.71

3. Con “viento solar” de velocidad < 460 km/s, 19 casos. Relaciones del flujo protónico con:

- the radioemission in centimetric band (S7, S9, S15, S7/S9)
- the heliolongitude “θ”
- solar wind density (Den)
- magnetic fiel component Bz

$$LogI7 = 1.01(LogS7) + 0.019\theta - 1.59 * 10^{-4}\theta^{2} + 0.047Den - 0.084Bz - 2.48$$

$$LogI9 = 0.97(LogS9) + 0.018\theta - 1.64 * 10^{-4}\theta^{2} + 0.046Den - 0.093Bz - 2.38$$

$$LogI15 = 0.92(LogS15) + 0.017\theta - 1.79 * 10^{-4}\theta^{2} + 0.037Den - 0.091Bz - 2.04$$

Correlation	E. Std
0.96	0.38
0.96	0.39
0.97	0.35

Soft Metric Radioemission Component Events

4. Without including the solar wind parameters, 41 cases. Proton flux relations with: the radioemission in centimetric band (S7, S9, S15, S7/S9) and the heliolongitude “θ”

$$LogI7 = 1.48(LogS7) - 1.81 * 10^{-4}\theta^2 + 2.73\frac{S7}{S9} - 5.85$$

$$LogI9 = 1.49(LogS9) - 1.84 * 10^{-4}\theta^2 + 3.40\frac{S7}{S9} - 6.57$$

$$LogI15 = 1.30(LogS15) - 1.97 * 10^{-4}\theta^2 + 3.50\frac{S7}{S9} - 5.84$$

Correlation	E. Std
0.74	0.74
0.75	0.74
0.79	0.68

5. When solar wind velocity is Vel < 460 km/s, 22 casos. Proton flux relations with:

- the radioemission in centimetric band (S7, S9, S15, S7/S9) and the heliolongitude “θ”
- solar wind density (Den) and velocity (Vel)
- magnetic fiel component Bx and the module of the component Bz

$$LogI7 = 1.14(LogS7) - 1.34 * 10^{-4}\theta^2 + 2.47\frac{S7}{S9} + 0.028Den - 0.0090Vel$$
$$- 0.081Bx - 0.26|Bz| - 1.07$$

$$LogI9 = 1.12(LogS9) - 1.35 * 10^{-4}\theta^2 + 2.95\frac{S7}{S9} + 0028Den - 0.0090Vel$$
$$- 0.079Bx - 0.26|Bz| - 1.54$$

$$LogI15 = 1.08(LogS15) - 1.72 * 10^{-4}\theta^2 + 3.02\frac{S7}{S9} + 0.025Den - 0.0075Vel$$
$$- 0.080Bx - 0.21|Bz| - 1.74$$

Correlation	E. Std
0.92	0.55
0.92	0.54
0.93	0.54

6. When solar wind velocity is Vel>460 km/s, 16 casos. Proton flux relations with:

- the radioemission in centimetric band (S7, S9, S15, S7/S9) and the heliolongitude “θ”
- solar wind density (Den) and velocity (Vel)
- magnetic fiel component By

$$LogI7 = 0.99(LogS7) + 0.0072\theta - 1.03 * 10^{-4}\theta^2 + 0.054Den + 0.32|By| - 3.20$$

$$LogI9 = 0.92(LogS9) + 0.0074\theta - 1.13 * 10^{-4}\theta^2 + 0.061Den + 0.34|By| - 3.07$$

$$LogI15 = 0.76(LogS15) + 0.0049\theta - 1.20 * 10^{-4}\theta^2 + 0.076Den + 0.34|By| - 2.50$$

Correlation	E. Std
0.95	0.35
0.95	0.35
0.94	0.36

Discussion

The nature information of these phenomena is in the obtained relationships, they confirm the conceptual validity of the model new version of the proton flux intensity prediction at the Earth environment.

It is clear the relationship dependence with the parameters of the radioemission and the heliolongitude in the 6 groups of relationships, that contain the information of the former model, including the results of the proton flux directivity mentioned in the Introduction, without contradictions.

Intense Metric Radioemission Component Events

The relationships 1 and 2 of the first square show the significant improvement of the adjustment when the term density is included for all solar wind parameter values.

The relationships of the group 2 show us an information that indicates the general behavior of these events, that respond to the resistance that can contribute a greater interplanetary media density to the acceleration of particles.

The mentioned effect is in correspondence with the observations like the case of the called "Cannibal Coronal Mass Ejection" in which an increase of the electromagnetic waves emission can be observed when a second coronal mass ejection propagate through a denser media due to an precedent ejection [Gopalswamy, N.; 2001].

While in the group of relationships 3 in which the interplanetary media state was characterized by a slow solar wind Vel < 460km/s, a significant improvement in the adjustment is obtained, showing a negative dependence of the magnetic field component Bz , being favorable the negative values of Bz to the enhancement of proton flux, that is the interplanetary media state in which there is magnetic connection with the geomagnetic field.

For the events that occurred in a interplanetary media state characterized by a fast solar wind Vel > 460km/s a significant improvement in the adjustment better than the relationships of the group 2 was not found and are not presented in this paper.

Soft Metric Radioemission Component Events

In the relations of the group 4 at the second square, a dependence is not only with the intensity of the radioemission, it also includes the dependence with the spectrum slope through the parameter S7/S9. And the heliolongitude quadratic dependence is symmetrical respect to the Sun central meridian, confirming the obtained results [Del Pozo 1998].

This answer lack to the asymmetry East-West due to the spiral structure of the interplanetary magnetic field, those make very different from the intense metric component events, and it indicates that these events not only differ in the corona propagation conditions, but also in the way that they go, interactuate and propagate in the interplanetary media.

In the relations of the groups 5 and 6 a significant improvement of the adjustment is observed when the proton events are analyzed for separate according to the interplanetary media state. For slow solar wind with speed Vel < 460 km/s and for fast solar wind with Vel > 460km/s. In both cases a significant improvement is obtained in the adjustment.

When the proton event takes place under conditions of slow solar wind, in the group 5 of relations appear besides the positive dependence with the density Den, the following relationships:

- The former detected negative dependence with the speed Vel [Del Pozo 2000], that can be interpreted as a consequence of the acceleration of particles due to a greater difference between the speed of the Sun output ejection and the speed of the previously emitted solar wind, since to smaller solar wind speed greater is the speed difference between these plasmas in interaction.
- A negative dependence of the magnetic field component Bx that favors the particle intensity flux when this component points from the Sun toward the Earth, which is in correspondence with that reported to the solar wind flux [Bothmer, 1998].
- A negative dependence of the modular value of the magnetic field component Bz that can be interpreted as an particle flux diverted element from the ecliptic plane.

On the other hand when the proton event takes place under conditions of fast solar wind, in the group 6 the following relationships appear:

- A small asymmetry is detected in the dependence with the heliolongitude through a term of first degree with a coefficient about three times minor that the coefficient in the intense metric component events relations
- The positive dependence with the density Den, but with a coefficient approximately twice that appear in the relation group 5
- A positive dependence of the By modular value of the magnetic field that can be interpreted as an collimator element, since the spiral structure of the interplanetary magnetic field is predominantly of component By near the ecliptic plane at the Earth neighborhood.

It is remarkable that in the relationships of the group 3 the intense metric component events that take place with slow solar wind, do not present dependence with the speed Vel, this can be related with the greater directivity and dependence of the asymmetry East-West due by spiral structure of the interplanetary magnetic field and with the different form in that these events input, interactuate and propagate in the interplanetary media,

Conclusions

The proton events present regularities that can be used to their prediction, at the same time that they show a diverse behavior in the generation process, irruption, interaction and propagation in the interplanetary media.

The obtained model allows advancing toward the implementation of a short term service of warning of the proton flux intensity, for intense and soft metric component events.

The obtained information allows to continue analyzing the physical processes that are present in these phenomena, that can improve the proposed relationships. At the same time they improve the bases for the future coordination of a “International Service of Proton Alert” that perform the diagnosis of the solar events and the prediction of the proton flux parameters 24 hours daily.

6. REFERENCES

Akinjian, S. T., V. V. Fomichev, And I. M. Chertok, (1977), Geomagnetism and Aeronomy, 17(1,2): 10-15; 177-183

Bothmer V. (1998) ESA Worshop On Space Weather, 11-15 November, Estec, Noordwijk, The Netherlands P.117-126

Claben H.T., et to the, 1998 A & A 335, 1101-1110

Classen A. et at the 2000, Suppl. A & A To be. 2000

Chertok, I. M., (1982): Geomagnetism and Aeronomy 22(2): 182-186

Del Pozo E., Chertok I.M. (1995), Retrospective Diagnose of the proton events of the period 1987-1990. Publication Stock of Documentation Institute of Scientific and Technical Information (IDIC)

Crosby, N.; Toivanen, P.; Heynderickx; Bothmer, V.; Gabriel, S.; Hildner, E.; Vilmer, N. (1998) "Working Group 2: Forecasting Space Weather - Scientific Road Map" European Space Agency, ESA Worshop on Space Weather, 11-15 November, ESTEC, Noordwijk, The Netherlands p. 521-524.

Del Pozo. E., Valiente J.F. (1996), Proceedings of IV Latin American Congress and Spaces Geophysic (COLAGE), (Eds) T. Heredia and A.G. Elías, Tucumám National University, Argentina.

Del Pozo E., Valiente J.F., (1998), V Latin American Congress on Space Geophysics (COLAGE) Costa Rica. Revista Geofísica 50 January–June 1999pp 119-126

Del Pozo E. , Valiente J.F., Días A., (1998 B), ESA Worshop On Space Weather, 11-15 November, Estec, Noordwijk, The Netherlands P.357-360.

Del Pozo et al, (2000) Scientific–Technician Report (2000)

Del Pozo et al, (2000a) "Solar Proton Flux Forecast" Scientific Comittee Solar on Terrestrial Physics, The First S-Ramp Conference Abstr., Oct 2-6 Sapporo Japan

Dyer, C. and Rodgers, D. (1998), "Effects On Spacecraft Electronics" European Space Agency, ESA Worshop On Space Weather, 11-15 November, Estec, Noordwijk. The Netherlands p. 17-27

Fomichev V.V., Chertok I.M., Del Pozo E., (1989): Geomagnetism and Aeronomy Vol. XXIX #4 PP. 537-544

Fomichev V.V., Chertok I.M., Del Pozo E., (1989a):, Idem. pp. 545-550

Gopalswamy, N., 2001; http://science.nasa.gov/headlines, March 27

Klein K. L., et to the, 2001; A & A 373, 1073-1082

Klein K. L., et to the, 2001b; Space Science Review 95; 215-225

Laitinen T., et al,:2000. A & A 360, 729-741

Reinier M. J., Fainberg J., Stone N.G. (1995), Science, Vol 270, P. 461-464.

Ryan, J.M.; Aikin, B.C. ;Cliver, E.W.; Reiger, E. and Share, G.H. (1998). "Solar-Terrestrial and Terrestrial Science" Book "The many Faces of the Sun" Chapter 14, p. 457-479

Solar Geophysical Dates (1966-2001): National Solar Geophysical Terrestrial Data Center, Boulder, Colorado,USA.

S-RAMP Conference, 2000; SCOSTEP, Sapporo, Japan; October 2-6

Valiente J.F., Del Pozo E. (1995), Diagnose in operative time of the proton events of the period 1991-1993. Publication Stock of Documentation Institute of Scientific and Technical Information (IDIC).

Vestrand, W. T.; Miller J. A., (1999) "Particles Accceleration in Flares", Book "The Many Faces of the Sun" Springer Verlag New York.

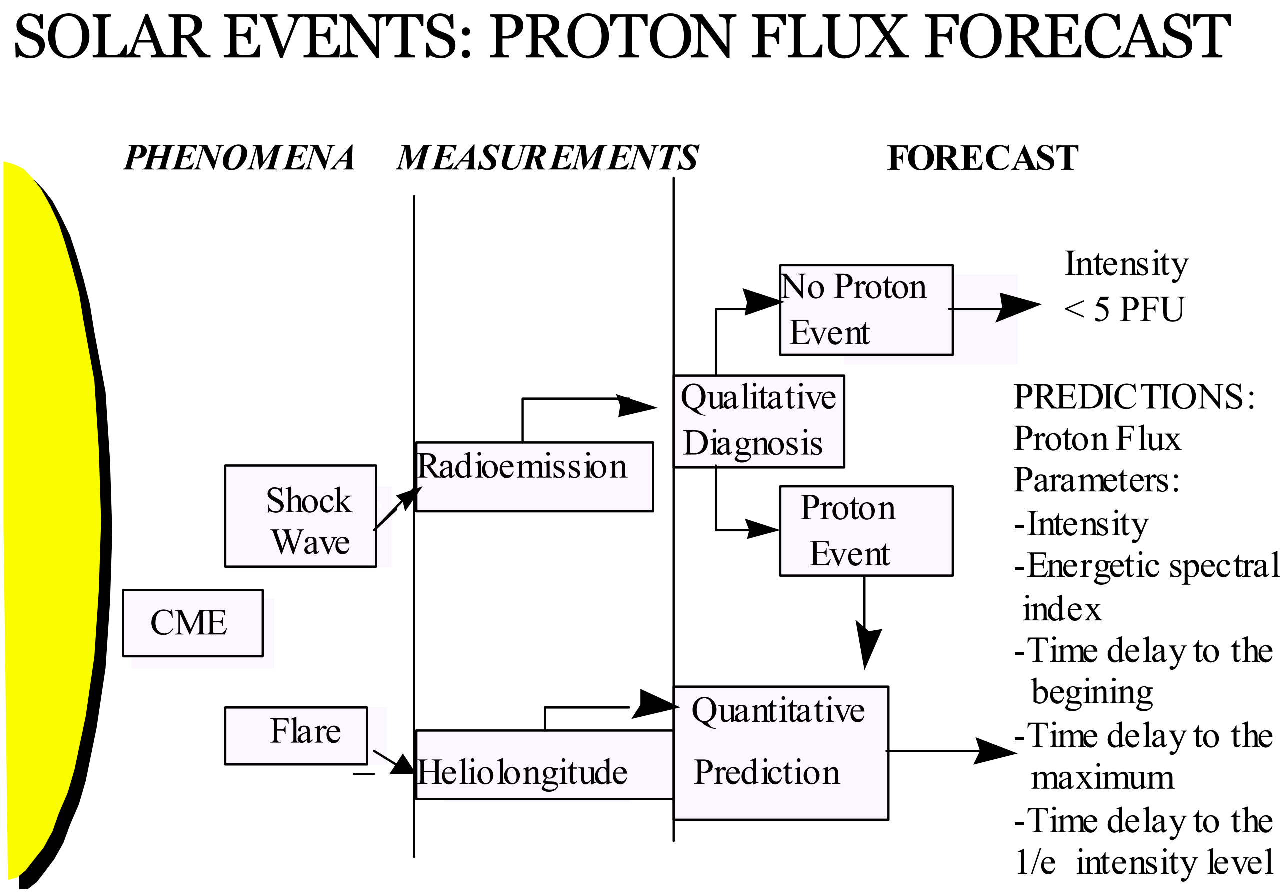

Figure 1: Initial Prediction model (1998)

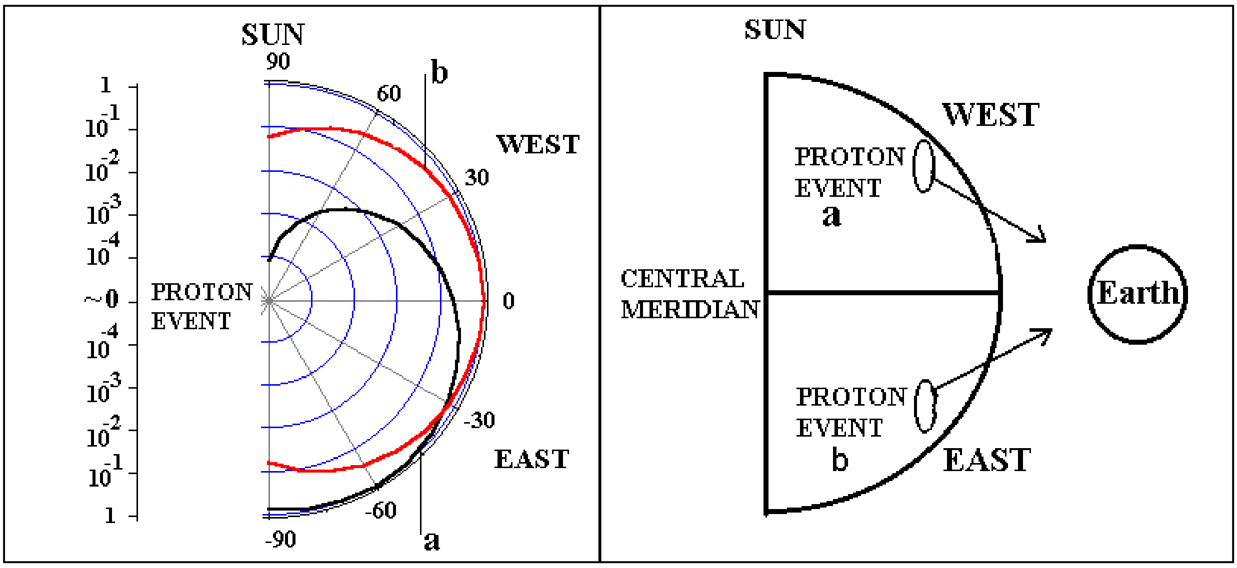

Figure 2: At the left directivity diagrams of the normalized intensity of the output proton flux of the proton event, when it has been located in the Central Meridian of the Sun

a - Diagram of the solar events of intense metric radioemission component

b - Diagram of the solar events of soft metric radioemission component

At the right proton events located in the positions P and Q in the Sun. To an event located at P the radiovector that points to Earth is at East side of the proton event directivity diagram, while to an event located at Q the radiovector that points to Earth is at Weast side of the proton event directivity diagram.

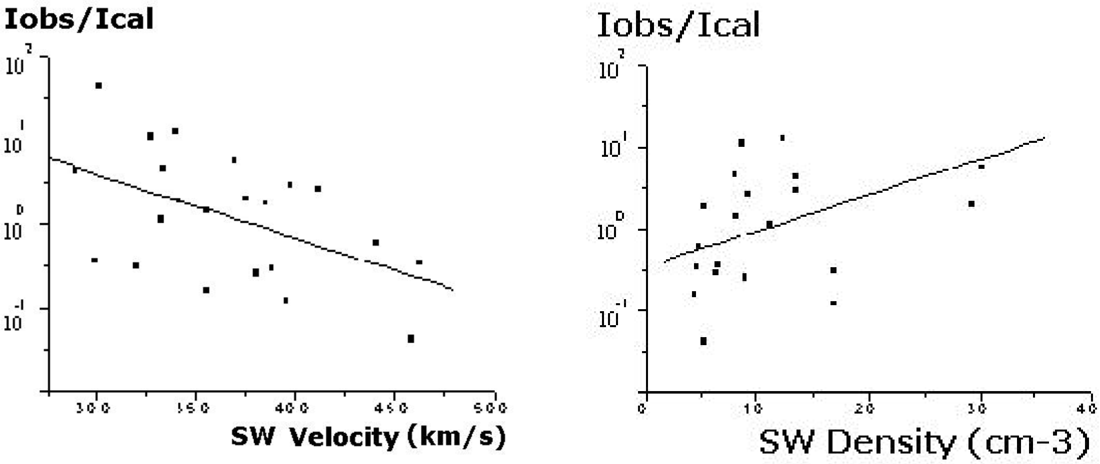

Figure 3: Evidences of the effect of the solar wind parameters of the in the proton flux intensity at the Earth neighborhood.

Figure 4: New version of the Proton Flux Prediction Model