Ionization Rates for 1963-2012 from Solar Proton Events

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Abstract: Large solar eruptive occurrences can lead to significant fluxes of protons at the Earth, which are called solar proton events (SPEs). Proton flux measurements during SPEs from satellites over the period 1963-2012 have been used to compute daily average ion pair production rates using an energy deposition calculation described below. These daily average ion pair production rates as functions of pressure between 888 hPa (~1 km) and 8 x 10^{-5} hPa (~115 km) are provided at the SOLARIS website (http:// http://sparcsolaris.gfz-potsdam.de/input_data.php) and can be assumed to affect the atmosphere approximately uniformly over both polar cap regions (60-90^{o}N and 60-90^{o}S geomagnetic latitude). Methodologies for deriving HO_x (H, OH, HO_2) and NO_x (N, NO, NO_2) production rates from these ion pair production rates are also given below.

1. Proton Flux and Ion Pair Production

Solar proton fluxes have been measured by a number of satellites in interplanetary space or in orbit around the Earth. The National Aeronautics and Space Administration (NASA) Interplanetary Monitoring Platform (IMP) series of satellites provided measurements of proton fluxes from 1963-1993. IMPs 1-7 were used for the fluxes from 1963-1973 [Jackman et al. 1990] and IMP 8 was used for the fluxes from 1974-1993 [Vitt and Jackman, 1996]. The National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES) were used for proton fluxes from 1994-2012 [e.g., Jackman et al. 2005a].

Proton flux data were taken from T. Armstrong and colleagues (University of Kansas, private communication, 1986) for the period 1963-1973 (see Armstrong et al. 1983 for a discussion of the IMP 1-7 satellite measurements). These data were fit with a power law form that was assumed to be valid over the range 5-100 MeV [Jackman et al. 1990] and then degraded in energy using the scheme first discussed in Jackman et al. [1980]. This energy degradation scheme assumes that the energy lost in each of the atmospheric slabs can be quantified using well-known range-energy relationships from Sternheimer [1959]. The scheme divides the protons into 60 monoenergetic energy intervals, all assumed to be isotropic, as well as 35 pitch angles. The scheme includes the deposition of energy by all the protons and associated secondary electrons. The energy required to create 1 ion pair was assumed to be 35 eV [Porter et al. 1976]. This energy degradation scheme has been compared with two other independent methodologies [Lummerzheim, 1992] and is found to be in good agreement with these other schemes.

IMP 8 was used for the proton flux data for the years 1974-1993. Vitt and Jackman [1996] take advantage of the measurements of alpha particles by IMP 8 as well and use proton fluxes from 0.38-289 MeV and alpha fluxes from 0.82-37.4 MeV in energy deposition computations. The energy deposition methodology is similar to that discussed in Jackman et al. [1980]. Alpha particles were found to add about 10% to the total ion pair production during SPEs.

Several GOES satellites are used for the proton fluxes in years 1994-2012: 1) GOES-7 for the period January 1, 1994 through February 28, 1995; 2) GOES-8 for the period March 1, 1995 through April 8, 2003, and May 10, 2003 to June 18, 2003; 3) GOES-11 for the period June 19, 2003 to April 13, 2010; 4) GOES-10 to fill in the gap of missing proton flux data from April 9 through May 9, 2003; and 5) GOES-13 for the period April 14, 2010 to December 31, 2012. The GOES satellite proton fluxes are fit in three energy intervals 1-10 MeV, 10-50 MeV, and 50-300 MeV with exponential spectral forms. The energy deposition methodology again is that discussed in Jackman et al. [1980].

Table 1. List of years, publication reference, and source of proton fluxes used in creating the ion pair production rates.

Years	Reference	Source of Protons
1963-1973	Jackman et al. [1990]	IMP 1-7
1974-1993	Vitt and Jackman [1996]	IMP 8
1994-2005	Jackman et al. [2005a]	GOES 7, 8, 10, 11
2006-2012	No reference	GOES 11 and 13

The daily average ion pair production rates are provided as functions of pressure between 888 hPa (~1 km) and 8 x 10^{-5} hPa (~115 km) at the SOLARIS website (http://strat-www.met.fu-berlin.de/~matthes/sparc/inputdata.html) and can be assumed to affect the atmosphere approximately uniformly over both polar cap regions (60-90^{o}N and 60-90^{o}S geomagnetic latitude). The datasets are divided into 50 individual yearly ASCII files labeled: *IonPair_Year_1963.dat…* *IonPair_Year_2012.dat* A fortran reader is provided labeled: *IP_read.f*

2. Odd Hydrogen (HO_x) Production

Along with the ion pairs, the protons and their associated secondary electrons also produce odd hydrogen (HO_x) and odd nitrogen (NO_y). The production of HO_x relies on complicated ion chemistry that takes place after the initial formation of ion pairs [Swider and Keneshea, 1973; Frederick, 1976; Solomon et al. 1981]. Solomon et al. [1981] computed HO_x production rates as a function of altitude and ion pair production. Some of these computations are given in Table 2 for background ion pair production rates of 10^2, 10^3, and 10^4 $cm^{-3}s^{-1}$. Each ion pair typically results in the production of around two HO_x constituents in the upper stratosphere and lower mesosphere. In the middle and upper mesosphere, an ion pair is computed to produce less than two HO_x constituents per ion pair.

Table 2. HO_x constituents produced per ion pair as a function of altitude for baseline ionization rates (BIR) of 10^2, 10^3, and 10^4 $cm^{-3}s^{-1}$. These HO_x production rates were taken from Solomon et al. [1981].

Altitude (km)	HO_x production per ion pair		
	BIR – 10^2 $cm^{-3}s^{-1}$	BIR – 10^3 $cm^{-3}s^{-1}$	BIR – 10^4 $cm^{-3}s^{-1}$
40	2.00	2.00	1.99
45	2.00	1.99	1.99
50	1.99	1.99	1.98
55	1.99	1.98	1.97
60	1.98	1.97	1.94
65	1.98	1.94	1.87
70	1.94	1.87	1.77
75	1.84	1.73	1.60
80	1.40	1.20	0.95
85	0.15	0.10	0.00
90	0.00	0.00	0.00

The SPE-produced HO_x constituents can be included in model simulations in the following way: Use an ASCII dataset (*HOx_Prod_Solomon.dat*) with a fortran reader (*HOx_Prod_Solomon.f*), which uses the Solomon et al. [1981] methodology in table form. These are located at the SOLARIS website:

http:// http://sparcsolaris.gfz-potsdam.de/input_data.php

3. Odd Nitrogen (NO_y) Production

Odd nitrogen is produced when the energetic charged particles (protons and associated secondary electrons) collide with and dissociate N_2. Following Porter et al. [1976] it is assumed that ~1.25 N atoms are produced per ion pair. The Porter et al. [1976] study also further divided the proton impact of N atom production between ground state (~45% or ~0.55 per ion pair) and excited state (~55% or ~0.7 per ion pair) nitrogen atoms. Ground state [$N(^4S)$] nitrogen atoms can create other NO_y constituents, such as NO, through

$$N(^4S) + O_2 \rightarrow NO + O \qquad (1)$$

or can lead to NO_y destruction through

$$N(^4S) + NO \rightarrow N_2 + O. \qquad (2)$$

Generally, excited states of atomic nitrogen, such as $N(^2D)$, result in the production of NO through

$$N(^2D) + O_2 \rightarrow NO + O \qquad (3)$$

[e.g., Rusch et al., 1981; Rees, 1989] and do not cause significant destruction of NO_y. Rusch et al. [1981] showed that there are huge differences in the final results of model computations of NO_y enhancements from SPEs that depend strongly on the branching ratios of the N atoms produced. If a model does not include any of the excited states of atomic nitrogen [e.g., $N(^2D)$, $N(^2P)$, and N^+] in their computations, the NO_y production from SPEs can still be included.

Here is a fairly accurate way to best represent the production of NO_y constituents by the protons and their associated secondary electrons [Jackman et al. 2005b]: Assume that 45% of the N atoms produced per ion pair result in the production of $N(^4S)$ (~0.55 per ion pair) and that 55% of the N atoms produced per ion pair result in the production of NO (~0.7 per ion pair).

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