THE MEAN IONIC CHARGES OF N, NE, MG, SI, AND S IN SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

The mean ionic charges of Nitrogen, Neon, Magnesium, Silicon, and Sulfur in solar flare particle events have been determined for 12 flares during the time interval from September 1978 to September 1979. The observations were carried out with the MPI/UoMd ULEZEQ Sensor on the ISEE-3 satellite Comparing the results with mean charge states established in a hot coronal plasma under equilibrium conditions, we derive different temperatures for different elements These range from approx $2 \cdot 10^6$K to $7 \cdot 10^6$K in a single flare From flare to flare the variation in temperature for each element is less than the variation between different ion species

1. Introduction The ionic charge state distributions of solar energetic particles provide important information about both the conditions at the source region and the nature of acceleration, coronal, and interplanetary propagation processes The processes involved in general depend on the particle's rigidity, thus, a knowledge of the particles mass to charge ratio A/Q is essential for comparing observations of solar energetic particles with theoretical models of acceleration and propagation processes Since charge states are not altered during the passage of the ions to earth[1], measurement of the charge state distributions can be used to diagnose the conditions of the plasma at the source region of the energetic particles

We report measurements of the mean ionic charges for the elements C, N, O, Ne, Mg, Si, S, and Fe in 12 flare associated solar energetic particle events in the time period from September 1978 to September 1979 Mean ionic charges of C, O, and Fe have been published before for all but two of the flares considered here[2,3] In [4] the other elements have been analysed for three of the flare events. For completeness these results are included in this work

2. Instrument and Data Analysis. The data presented in this paper heve been obtained with the Max-Planck-Institut / University of Maryland ULEZEQ Sensor onboard the ISEE-3 spacecraft During the period of the measurements from September 1978 to October 1979 this satellite was positioned at the Lagrangian point L_1 between the Earth and the Sun, at a distance of about 230 R_E from the Earth By combining an electrostatic deflection system with a position sensitive solid

state detector and a proportional counter, the ULEZEQ sensor is capable of determining seperately the energy E and nuclear charge Z of an incoming ion in the energy range from ~0 3 to ~4 MeV/nucleon as well as measuring it's ionic charge Q Because of the poor counting statistics, especially for the rarer elements (N, Ne, Mg, Si, and S) and the limited charge resolution of the sensor, we present only the mean values of the charge state distributions The determination of the ionic charge is, apart from statistical errors, subject to a systematic uncertainty of less than 5% The resolution of the sensor with respect to elemental species is such that within the iron group, individual elements cannot be seperated However, since most particles in this group are in fact iron, we stay with the common practice to designate them by "Fe" For a detailed description of the sensor and data analysis see Hovestadt et al [5].

For our analysis we selected 12 well identified flare associated solar energetic particle events from September 1978 to September 1979 (see Table 1) The start and end times for the accumulation periods were chosen as to maximize the counting statistics, that is from the onset of the energetic particle flux well into the declining phase We assume here that the charge states are not affected by post-acceleration of the flare generated shock wave during the passage to earth. The energy ranges for the accumulation of the different elements represent a compromise between charge resolution and counting statistics They are 0 45-2 34 MeV/N for C, 0.45-2 62 MeV/N for N, 0 54-2 64 MeV/N for O, 0.56-3 14 MeV/N for Ne, 0.56-3.37 MeV/N for Mg, 0.55-2.97 MeV/N for Si, 0.55-3.17 MeV/N for S, and 0.34-1 78 MeV/N for Fe

Table 1. *Selected SEP events*

ID	Accumulation period
1	1978 doy 266,12 00- 271,00 00
2	doy 314,06·00- 321,00 00
3	doy 346,06.00- 355,00 00
4	1979 doy 48,18 00- 55,06·00
5	doy 87,06.00- 90,00.00
6	doy 93,12 00- 98,00 00
7	doy 113,06 00- 117,12 00
8	doy 147,12.00- 152,12.00
9	doy 157,06.00- 165,00.00
10	doy 213,06 00- 218,00·00
11	doy 231,12 00- 239,00 00
12	doy 258,06 00- 272,00·00

3 Results and Discussion · In Table 2 we summarize the results for the mean charges in all of the observed flares. We also give the weighed average of the 12 periods From the measured mean charge and ionization equilibrium tables[6,7,8,9] one can derive for each ion the electron temperature of the source plasma of these ions This should give consistent results if the following assumptions hold 1) Conditions are such that charge equilibrium can be established, 2) the distribution function of the plasma electron is a Maxwellian (this is asumed in the calculation of the tables), and 3) charge exchange processes are negligible during acceleration and propagation. As an example we show in Fig 1 mean equilibrium charge states as a function of temperature for O, Ne, Mg, Si, and S. The values of the mean charge for accumulation period 1 are indicated by heavy lines For the elements shown as well as for C and N there is no difference in the mean values of the charge state distributions as calculated from the tables of Jordan ([6,7]) and Shull and van Steenberg ([8,9]) above temperatures of $\lesssim 10^6$K We do not show Iron, because for this ion the difference in the inferred temperatures for the two tabulations is significant We attribute this to the inherent difficulties in estimating the ionization and recombination rates for a many electron system (as Iron in this temperature range) and the errors introduced in the simple analytical interpolation formulæ for the rate coefficients used in [8] In Fig 2 we compile

Table 2 *Mean charges in solar energetic particle events*

period ID	mean charge							
	C	N	O	Ne	Mg	Si	S	Fe
1	5 76 ± 0 05*	6 31 ± 0 11	7 13 ± 0 04	9 23 ± 0 15	10 8 ± 0 16	11 1 ± 0 21	11 2 ± 0 42	14 4 ± 0 16
2	5 90 ± 0 06	6 59 ± 0 13	7 17 ± 0 05	9 20 ± 0 25	11 4 ± 0 20	12 0 ± 0 31	10 5 ± 0 47	16 3 ± 0 24
3	5 79 ± 0 09	6 53 ± 0 16	7 19 ± 0 06	9 53 ± 0 29	11 0 ± 0 28	11 9 ± 0 37	12 9 ± 1 31	15 7 ± 0 26
4	5 66 ± 0 13	6 74 ± 0 26	7 11 ± 0 11	9 74 ± 0 27	10 5 ± 0 38	11 5 ± 0 67	—	17 7 ± 0 62
5	5 81 ± 0 16	7 06 ± 0 41	6 76 ± 0 16	8 89 ± 0 88	11 2 ± 0 69	10 0 ± 0 82	—	12 2 ± 1 35
6	5 72 ± 0 05	6 37 ± 0 09	7 01 ± 0 04	9 06 ± 0 16	10 7 ± 0 16	11 4 ± 0 28	11 0 ± 0 82	15 1 ± 0 24
7	5 82 ± 0 07	6 79 ± 0 14	7 05 ± 0 10	9 14 ± 0 44	10 6 ± 0 36	11 7 ± 0 17	—	13 6 ± 0 86
8	5 80 ± 0 15	6 25 ± 0 34	6 89 ± 0 18	9 47 ± 0 48	9 72 ± 0 70	11 7 ± 1 41	—	16 3 ± 1 34
9	5 59 ± 0 04	6 19 ± 0 07	6 83 ± 0 04	8 77 ± 0 14	10 4 ± 0 15	9 83 ± 0 23	9 55 ± 0 90	14 2 ± 0 22
10	5 58 ± 0 16	6 65 ± 0 43	7 10 ± 0 20	8 46 ± 0 71	10 2 ± 0 67	—**	—	14 5 ± 0 51
11	5 62 ± 0 07	6 34 ± 0 17	6 84 ± 0 06	8 91 ± 0 21	10 5 ± 0 24	10 6 ± 0 33	11 2 ± 0 59	14 7 ± 0 26
12	5 40 ± 0 11	6 25 ± 0 22	6 71 ± 0 12	8 21 ± 0 48	10 8 ± 0 53	11 1 ± 0 57	8 97 ± 1 25	14 6 ± 0 74
average	5 70 ± 0 02	6 37 ± 0 04	7 00 ± 0 02	9 05 ± 0 07	10 7 ± 0 07	11 0 ± 0 10	10 9 ± 0 24	14 9 ± 0 09

* Errors are 1σ statistical errors only Additionally, the mean charges are subject to a systematic error of ≤ 5%

** No values are given if less than 3 counts are detected

the inferred equilibrium temperatures for all of the 12 periods It is evident that 1) different elements aparently reflect different equilibrium temperatures and 2) these values remain fairly constant from flare to flare This is a strong indication that at least one of the above three assumptions is not applicable

Recently calculations have been performed to allow for 1) non steady state charge states and 2) a non-Maxwellian tail of the electron distribution function determining the charge state distributions ([10]), as well as 3) for charge states by interactions of fast ions with a hot coronal plasma ([11]) Neither of these relaxations from the original assumption of charge equilibrium can explain the observed variations in the mean charge states for the different elements To resolve this discrepancy one possibly has to invoke a combination of the above three effects and also take into account the x-ray radiation field, which is neglibible in the quiet solar corona, but might not be in solar flares [12].

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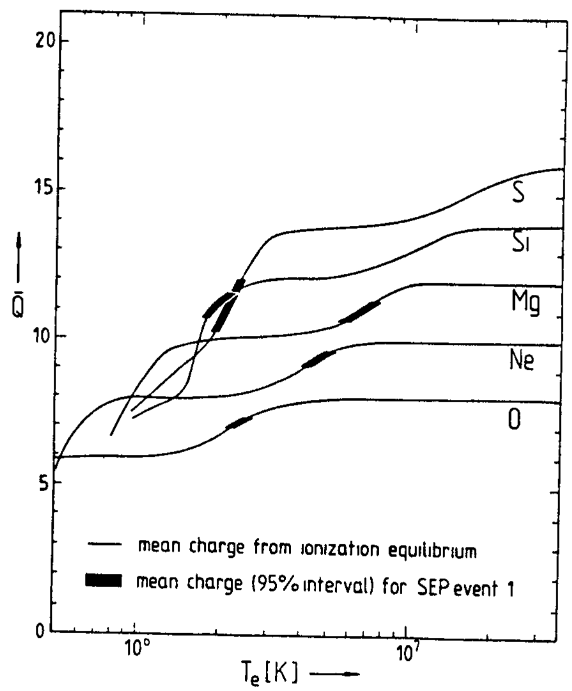

Fig 1 *Mean charge of O, Ne, Mg, Si, and S as a function of temperature as calculated from [8,9]. Heavy lines mark the temperature ranges compatible with the 95% confidence interval of the charge state measurements of solar energetic particle event 1*

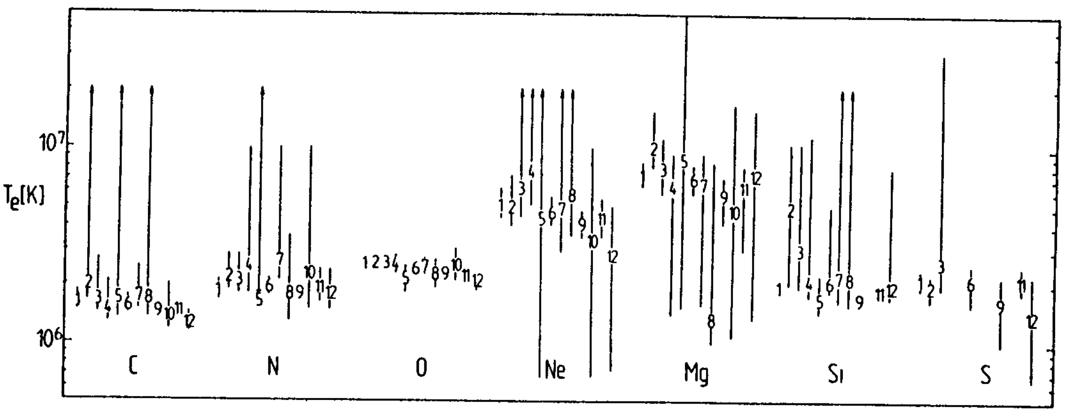

Fig 2 *Equilibrium temperatures (95% confidence intervals or lower limits) for the 12 SEP periods of Table 1, derived from [8,9].*

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