



Solar Energetic Particle Events with High Iron Charge State throughout ACE SEPICA Energy Range



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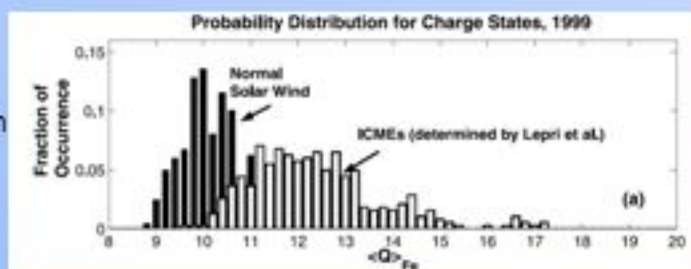
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Introduction

- Solar Energetic Particle events usually are categorized by types, gradual and impulsive events
- Gradual events show $Q_{Fe} = 9-11$, compatible with the corona temperature
- Impulsive events are observed with $Q_{Fe} \approx 20$ (Luhn, 1987), at that time interpreted as from a high temperature source
- With ACE, more detailed studies show energy dependent charge states in impulsive events that Q increases with energy and at lower energies it is consistent with a source temperature of 1-3 MK
- However, solar wind from active regions consistently contains iron charge states >16

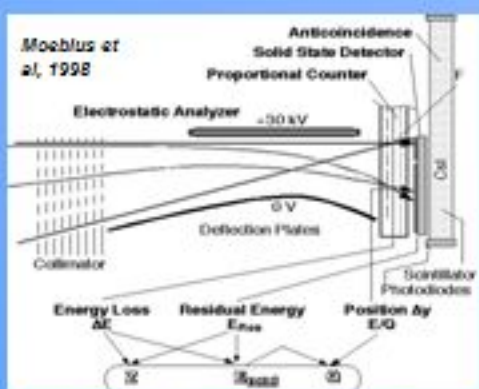


Lepri and Zurbuchen, 2004

In this study, we search for SEP Events with high Fe charge states at low energies to see whether ions from high temperature sources are accelerated

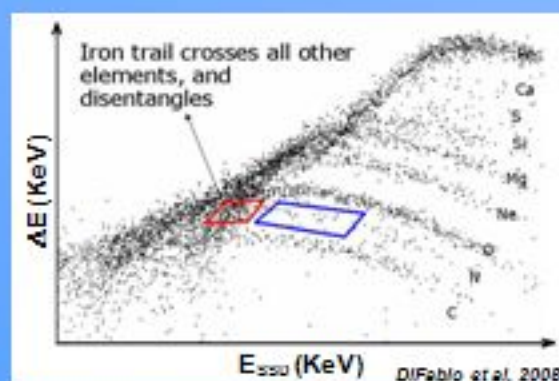
Instrument

ACE SEPICA can obtain direct charge state for SEP events



Solar Energetic Particle Ionic Charge Analyzer (SEPICA) on ACE

- Selection in E/Q through Electrostatic Analyzer
- Species Selection by ΔE versus E Analysis in Proportional Counter/ Solid State Detector (SSD) Combination
- Measurement of Total Energy E as Sum of Residual Energy in SSD, Energy Loss in Proportional Counter, and Energy Losses in Various Windows
- Calculation of Q as $Q = E/(E/Q)$
- Nominal energy range: 0.18-0.54 MeV/n for Fe



Charge state calculation of Fe for an extended energy

- Species determination becomes hard for low energies where trails blend
- Fe trail crosses O, but re-emerges at even lower energy
- Only a small N contamination is present; after subtraction, Q_{Fe} is calculated in extended energy range: 0.062-0.11 MeV/n

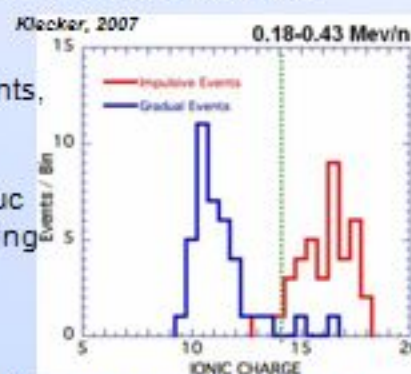
DiFabio et al, 2008

Data selection and analysis

The search of High source temperature in the entire SEP energy range

Approach 1: Q_{Fe} from SEPICA

- Survey a total of 89 strong SEP Events during year 1998 - 2000
- Events are chosen based on their flux of 0.23-0.33 MeV/n, a conservative energy range away from SEPICA high and low energy limits
- Q_{Fe} are then studied in all regular SEPICA energy channels
- $Q_{mean} = 14$, used as division between gradual and impulsive events, is also used here
- Find events with $Q_{Fe} > 14$ at 0.18-0.25 MeV/n
- Analyze for high Q_{Fe} at the extended energy of 0.06-0.11 MeV/nuc
- Impulsive events are excluded as a first cut as they show stripping feature and may have lower Q_{Fe} at even lower energy ranges.



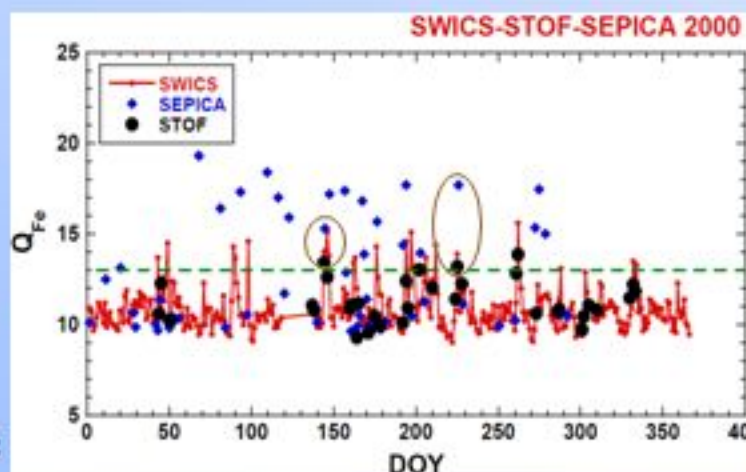
Mean Q_{Fe} for SEP events

Over 3 Years, 2 events found

with $Q_{mean} > 14$ in the lowest SEPICA energy (0.062-0.11 MeV/nuc):
 1998 DOY 101.9 - 103.5
 1998 DOY 158.25 - 160.5

Approach 2: Combining data from ACE SEPICA, SWICS and SOHO STOF

- Compare Q_{mean} in 89 SEPICA events to correspondent daily Q_{Fe} averages in solar wind with ACE SWICS and at 10-100 keV/n with SOHO STOF
- STOF Q_{Fe} are usually consistent with SWICS solar wind Q_{Fe}
- SEPICA Q_{Fe} either consistent with SWICS SW Q_{Fe} or much higher (Impulsive cases)



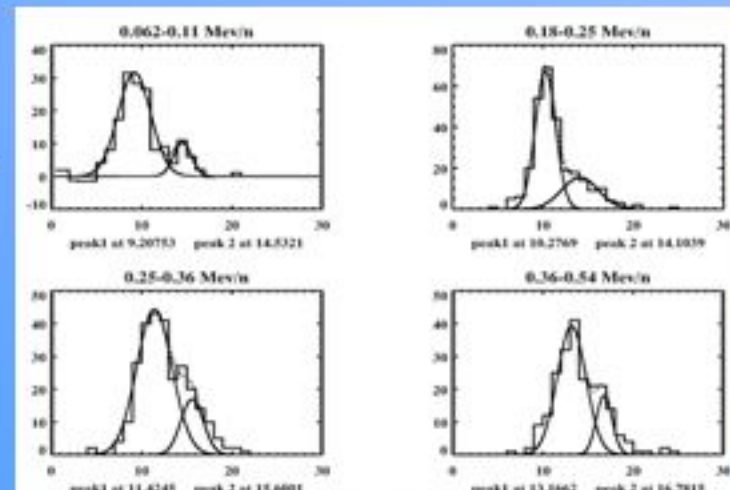
Compiled plot for Mean Q_{Fe} of ACE SEPICA, SWICS and SOHO STOF

Over 3 Years, 3 events found With $Q_{Fe} > 13$ SEPICA, SWICS & STOF:

1998 DOY 124.25-125.292
 2000 DOY 144.8 - 145.99
 2000 DOY 225.75 - 226.1

Approach 3: Isolation of high Q component in multi-population events

- Events with multiple seed populations may show a low mean charge state However, one component may show high Q_{Fe} over the entire SEP energy range in such events



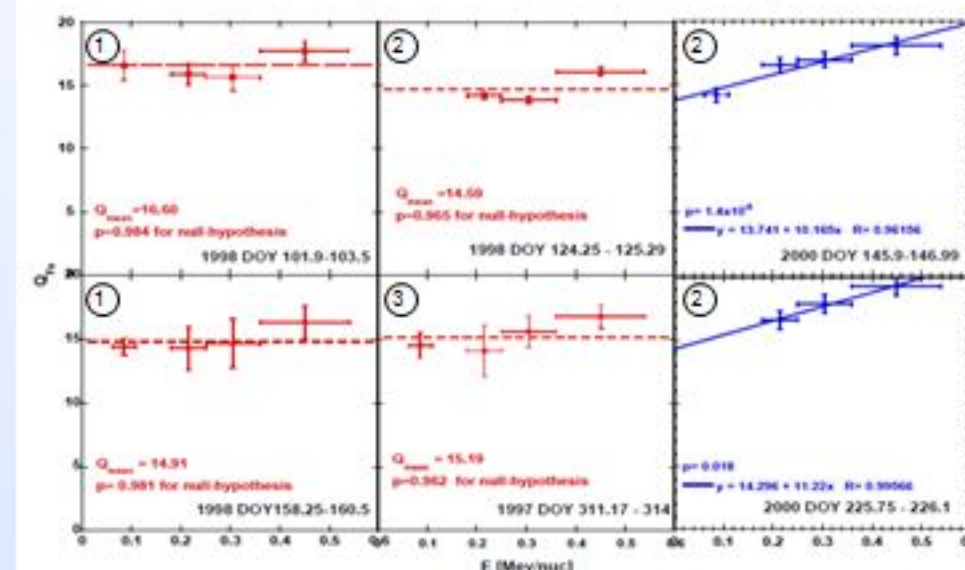
Double Gaussian fit on the charge state distribution in each SEPICA energy channel of 1997 311.25 - 314 event

- With the SEPICA high resolution fan (available during first few months of ACE) multi-Gaussian fits could be used to separate Q distribution components
- SEP event of DOY 311.25 - 314, 1997, has been successfully separated into 2 seed populations
- 1st component: $Q_{Fe} \sim 9$ at lower energy, increases with energy consistent with stripping
- 2nd component: $Q_{Fe} > 14$ throughout

Over 3 Years, 1 event found With $Q_{Fe} > 14$ component:
 1997 DOY 311.25 - 314.97

Results and discussions

In a 3 year period and out of more than 89 SEP events, 6 events are found with $Q_{Fe} > 14$ even in the lowest SEPICA energy range, in 5 of them for the entire event, in 1 of them just for one component



E-Q plot of all 6 events that we have found. Circled numbers represents which approach is used

- Two different trends with energy are seen in the charge states:
- 2 of the 6 events were identified as impulsive events by DiFabio et al, 2008. Increase of Q with energy is statistically significant ($p < 0.1$), consistent with stripping. However, starting at the lowest energy Q_{Fe} is still >14 .
- 4 of the 6 events with high Q at low energy show an essentially flat behavior with energy. The Chi-square test result is consistent with a random distribution of points around Q_{mean}

What is the high Q_{Fe} related to that we see?

- It indicates a high temperature source of 2-6 MK
- Consistent with Solar Wind observations
- Search for sources of these events: Possible characteristics of both impulsive and gradual events are found, while nothing conclusive.
- Only thing in common for these events is the enhancement in abundance of heavy ions, which seems to be an impulsive indicator, but this is not conclusive either according to Desai et al, 2001.

Event No.	1	2	3	4	5	6
Year	1998	1998	1998	2000	2000	1997
Time Period (DOY)	101.9-103.5	124.25-125.29	158.25-160.5	145.9-146.97	225.75-226.1	311.26-314
Shock/CME related origin	ACE/WIND shock list					DOY 310 & 313
	Solar Wind Compression region					
	SOHO LASCO CME list	2 poor DOY 99	1 DOY 123	1 poor DOY 156		DOY 308 & 310
Impulsive related origin	Election injection		Yes			Yes
	Injection	Yes			single	multi
	NOAA Flare Archive					2 flares
	Q increase in E heavy ions enhanced	Yes	Yes	Yes	Yes	Yes

- High Q at low energy could also be a result of adiabatic deceleration that pushes high Q from high to low energy. --- very unlikely.
- requires over expansion of solar wind, and still a raise in charge state to even higher Q_{Fe} . Neither is observed.

Conclusion

- A confirmed high Q_{Fe} over the entire energy range of SEPICA is found for 6 out of over 89 SEP events.
- While active regions are usually related to SEP events, the SEP events with high Q are pretty rare.
- This observation of high Q_{Fe} in SEP events is consistent with solar wind observations However only 3 in of 6 cases are these high charge states observed simultaneously in solar wind and SEP events.
- We are not able to find a consistent source and acceleration mechanism for all these events.

Acknowledgements

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