THE MEAN IONIC CHARGE OF SILICON IN ^{3}HE-RICH SOLAR FLARES

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ABSTRACT

In addition to the previously reported mean ionic charge of Iron in ^{3}He-rich solar flares we have for the first time determined the average mean charge of Silicon for 22 ^{3}He-rich periods during the time interval from September 1978 to October 1979 The results indicate that the value of the mean charge state of Silicon is higher than the normal flare average by approximately 3 units and in particular it is higher than the value predicted by resonant heating models for ^{3}He-rich solar flares

1. Introduction. The ^{3}He isotope was first measured as a constituent of solar energetic particle events in 1970 by Hsieh and Simpson [1]. Following this discovery, it has been firmly established by now that there exists a class of generally small solar flare events in which the abundance of the ^{3}He isotope relative to ^{4}He in solar cosmic rays is greatly enhanced relative to the normal solar abundance ratios. Enrichments of more than four orders of magnitude have been observed, leading to a ^{3}He/^{4}He ratio of $\gtrsim$ 1 These unusually high enrichment factors can best be explained by a two-stage acceleration process with a first step highly selective in mass per charge and a second step acting only upon particles above a certain threshold in rigidity or velocity Several plasma heating processes have been proposed as the first stage ([2,3,4,5]), which preferentially heat certain minor ion species like ^{3}He The effect of the preferential heating will be most pronounced in the tail of the ion distribution function The second stage acceleration process will then (apart from introducing additional abundance changes, see [6]) mainly reflect the abundance ratios in the tails of the ion distribution functions In all of the proposed heating processes the ionic charge states play a critical role for the largest attainable particle velocity and/or the heating rate Measurements of the charge states of energetic ions in ^{3}He-rich events are therefore crucial in understanding the nature of the enrichment process For recent reviews of observational and theoretical aspects of ^{3}He-rich flares see e.g [7,8].

2. Instrument and Data Analysis. The data presented in this paper have been obtained during the period from September 1978 to October 1979 with the Max-Planck-Institut / University of Maryland ULEZEQ Sensor onboard the ISEE-3 spacecraft (see also [8]) The instrument is described in more detail by Hovestadt et al [10]. We performed the charge analysis of Fe and Si for 22 periods rich in ^{3}He as determined from a systematic study of the composition of solar energetic particles with our wide angle particle telescope (ULEWAT) on the same spacecraft We selected periods with a ^{3}He/^{4}He ratio of $\leq$ 0 1, lasting more than one day. The average ^{3}He/^{4}He ratio of all 22 periods is 0.227. The energy range for which the charge analysis for Si and Fe is performed, is 0.55-3.0 and 0.34-1.8 MeV/N respectively. This represents a compromise between elemental and charge resolution and counting statistics

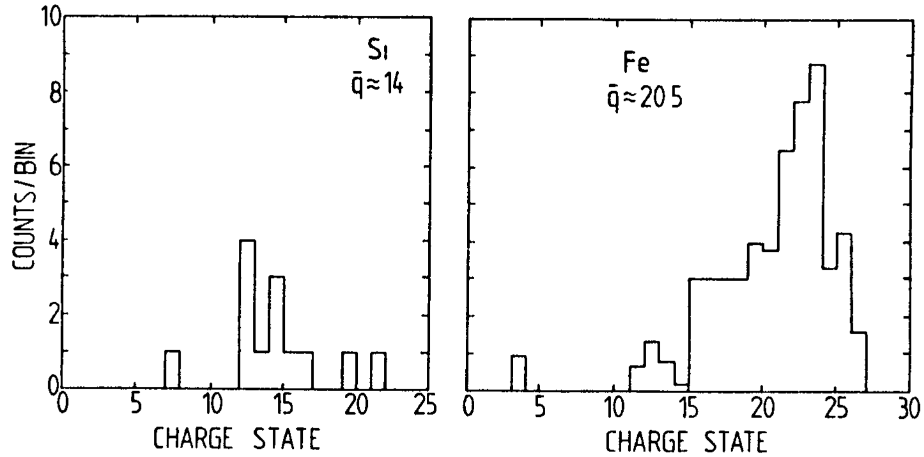

Fig 1 *Measured charge state distributions of Si and Fe for ^{3}He-rich energetic particle events*

3. Results. Because of the poor counting statistics for heavy ions in the ^{3}He-rich energetic particle events, it is impossible to give mean charge states for individual events Instead, we have to accumulate the pulse height data for all of the observed events and derive an average charge state distribution. Still, we have only registered a total of 13 Silicon and 56 Iron ions Fig 1 shows the resulting charge state histograms The mean charge for Fe is 20.6±1.2 (95% confidence level). Compared to the average charge of 14 9±0 2 for normal solar energetic particle events[9], it is significantly higher for this class of flares, confirming the result of Klecker et al.[11,12] for a subset of ^{3}He-rich periods The mean charge of Si is much less well determined The value calculated from the measured distribution is compatible with fully ionized Si ions In order to find lower boundaries for the mean charge, we performed a t test and obtain values of 12 6 and 11 7 for confidence levels of 95% and 99% respectively Again this has to be compared with a value of 11.0 ± 0.2 for normal flares. Although the statistical significance is less than in the case of Fe, one can conlude that also

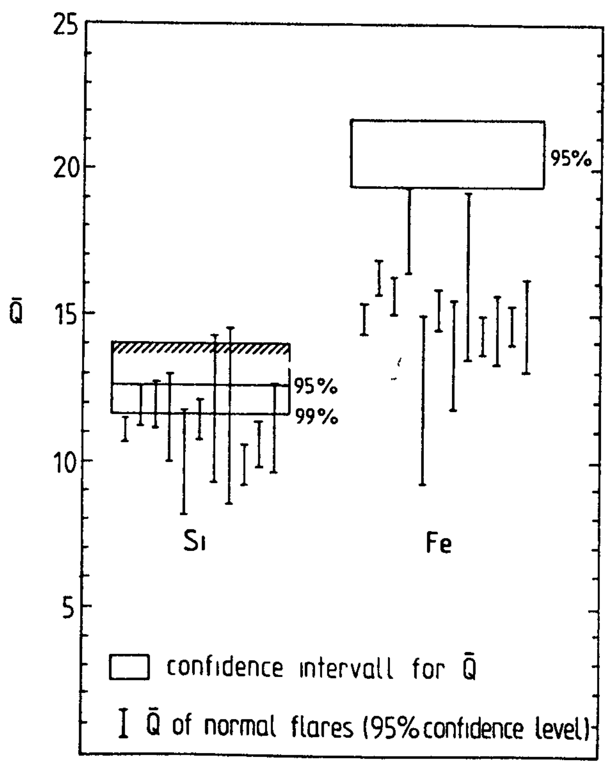

Fig 2 *Confidence levels for the average charge in ^{3}He-rich periods compared with results for normal flares (9).*

Si shows higher charge states in ^{3}He-rich flares Fig 2 gives the confidence intervals of the mean charges for Si and Fe together with results from normal flares It should be noted that in addition to the statistical errors quoted above, the mean charges are subject to a systematic error of 5% However this does not affect the comparison between this result and the mean charges of normal flares, since both measurements have the same systematic error

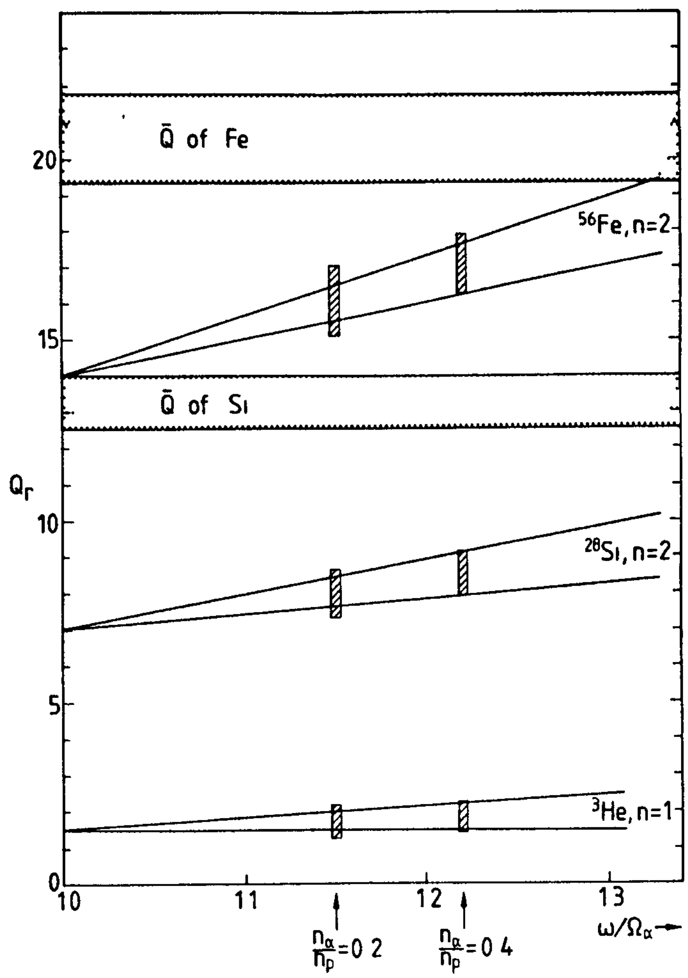

Fig 3 *Allowed ranges of the ionic charge for resonant heating by He-cyclotron waves as a function of the wave frequency ω/Ω_α*

4 Discussion We will concentrate on the comparison of the measurements with the implications of Fisk's [3] model for the preferential heating of ^{3}He For a discussion of the other processes see [12] Fisk employs resonant heating by electrostatic ion cyclotron waves in connection with a second stage acceleration process as described in the introduction to account for the ^{3}He enrichment factors observed The condition for resonant interaction of an ion (mass m_i, charge q_i, velocity $v_\parallel$ parallel to the magnetic field B, gyrofrequency $\Omega = q_i B/m_i c$) with a wave of frequency ω and parallel wavenumber $k_\parallel$ is given by

$$|(\omega - n\Omega)/(k_\parallel v_\parallel)| = 1 \qquad (1)$$

n is the number of the harmonic of the interaction To be in resonance with the first harmonic of the gyrofrequency of ^{3}He requires He-cyclotron waves with a frequency $\omega \sim 1\ 2\ \Omega_\alpha$, Ω_α being the gyrofrequency of ^{4}He To determine the charge states of heavy ions which interact resonantly with the wave, we follow Mason et al [13] in setting $v_\parallel = (k_B T/3m_i)^{1/2}$ and requiring a value of $k_\parallel$ such that the bulk of the wave-supporting ^{4}He distribution does not fulfill the resonance condition (1) We then obtain the following expression for the resonant Q/A ratio (Q=charge in units of e, A=atomic mass number of the ion)

$$2\frac{\omega}{\Omega_\alpha}\left[1 - \frac{2}{\sqrt{A}}\left(1 - \frac{1}{4\,\omega/\Omega_\alpha}\right)\right] < n\frac{Q}{A} < 2\frac{\omega}{\Omega_\alpha}\left[1 + \frac{2}{\sqrt{A}}\left(1 - \frac{1}{4\,\omega/\Omega_\alpha}\right)\right] \qquad (2)$$

In Fig 3 we plot the allowed range of the resonant charge Q_r, satisfying (2), as a function of the wave frequency The hatched vertical bars represent the regions of Q_r calculated from a numerical solution of the dispersion relation for an electrostatic ion cyclotron wave in a Hydrogen - Helium plasma for two different values of the relative Helium concentration n_α/n_p [14]. Shaded regions mark the 95% confidence interval for the observed average mean charges Resonant heating of Fe via the second harmonic would require charge states of approx 16 to 18, whereas for Si one would expect charge states around 8 to 9 (see also [13]) Despite the poor counting statistics for Si, a mean charge of 8 to 9 is not compatible with the observations For Fe too the measured mean charge is higher than that required for resonant interaction However, the width of the charge distribution is wide enough to extend down to the resonant charge states. One may therefore conclude that if indeed the Fisk mechanism is acting as a first stage heating mechanism, it cannot be the only one Significant portions of the source plasma of the energetic particles must stem from a different, as yet unspecified injection process The high charge states of both Fe and Si imply a temperature of $\sim 10^7$K in the source region of ^{3}He-rich flares This is significantly higher than temperatures of $\sim 3 \cdot 10^6$K derived from Si and Fe charge states in normal flares[9] A high temperature at the source region of ^{3}He-rich flares also excludes selective heating by ion acoustic turbulence as proposed by Kocharov[4], because in this model the heating site is located at the upper chromosphere with an ambient temperature of $\sim 10^5$K ([8])

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References

1. K.C Hsieh, J.A Simpson Ap J Lett **162**, L191 (1970)
2. J.A Ibragimov, G.E Kocharov Proc 15th Int Cosmic Ray Conf. (Plovdiv), **12**, p 221 (1977)
3. L.A. Fisk Ap. J **224**, p 1048 (1978)
4. L.G. Kocharov Proc. 17th Int. Cosmic Ray Conf (Paris), **3**, p 175 (1981)
5 H Varvoglis, K Papadopoulos Ap J. Lett **270**, L95 (1983)
6 E Mobius et al Ap J **238**, p 768 (1980)
7 C Y. Fan et al Space Science Rev **38**, p 143 (1984)
8 L.G Kocharov, G E Kocharov Space Science Rev **38**, p 89 (1984)
9 A Luhn et al paper SH 2 1-11 (this conference)
10 D Hovestadt et al. IEEE Trans Geos Electr **GE-16**, p 166 (1978)
11. B Klecker et al Ap J **281**, p 458 (1984)
12 B. Klecker et al.. Proc 18th Int Cosmic Ray Conf (Bangalore), **4**, p 65 (1983)
13 G. Mason et al · Ap. J **239**, p 1070 (1980)
14 A Luhn, Ph.D Thesis, Technische Universität Munchen (1985)