MIXED SOLAR WIND ORIGINATING FROM CORONAL REGIONS OF DIFFERENT TEMPERATURES

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ABSTRACT

Ionization states of elements in the solar wind have been used to determine thermal gradients in the lower corona. This method is based on the assumption, that in the beginning, solar wind material has a homogeneous temperature determining the original charge state of elements. In this paper, we investigate features in M/Q-spectra which might appear if the above assumption is violated and compare them with observational evidence.

INTRODUCTION

There is evidence for several cases of simultaneous appearance of $^4He^+$ and highly charged ions of other elements such as O^{6+} in low speed solar wind [Bame et al., 1968; Schwenn et al., 1980; Gosling et al., 1980; Zwickl et al., 1982] indicating the existence of mixtures of plasma with states of ionization frozen in at temperatures which differ by orders of magnitude. The mechanisms inherent in solar wind acceleration and heating which lead to these observations are not well understood. He^+ has a large cross section for complete ionization via electron collision at coronal temperatures. Typical rates for collisional ionization of He^+ are of the order of $10^{-8}\,cm^3\,s^{-1}$ in the corona [Lotz, 1967]. This makes it obvious, that He^+ can only reach the outer part of the corona if it is somehow separated from the ambient hot plasma in the lower corona. A plausible way to achieve this separation is inclusion of the cold component into magnetic clouds [Zwickl et al., 1982]. Such clouds have been observed in connection with coronal mass ejections [Klein and Burlaga, 1982], but to our knowledge not with enrichments in $^4He^+$ in the solar wind. Hovestadt et al. [1982] find, that He^+ in an energetic solar proton event is far more abundant than expected when related to the mean charge states of C, O, and Fe.

From observations of EUV spectra in coronal loops there is evidence that these structures are cooling so rapidly that departure from thermal equilibrium occurs quite frequently [Raymond and Foukal, 1982]. Eruption of such loops into the corona will eventually provide mixtures of low and high ionization states as occasionally observed in $^4He^+$-rich events.

Detection of $^4He^+$-rich events by means of E/Q- or M/Q-analyzers is in principle possible as long as $^4He^+$ is at least as abundant as the underlying ion Si^{7+}

which is usually the most prominent contributor at M/Q = 4.0. Only very few events of this type have been detected up to now; however this does not a priori preclude the possibility that these events are only extreme and rare cases of a more common phenomenon. In other words, it is possible that mixing of plasma from regions of different coronal temperatures occurs quite frequently in solar wind emanating from regions near sector boundaries and that generally, the degrees of ionization of the components involved in these mixtures do not differ to such a large extent as in the rare cases where $^4He^+$ is detectable.

The purpose of this study is to explore how such "moderate" mixtures without appearance of $^4He^+$ might be detected in M/Q-spectra of low speed solar wind. Specific features which can be attributed to plasma mixing will be critically discussed and investigated for uniqueness, i.e. we also look into mechanisms, other than plasma mixing, which could produce similar indicators as those found for mixing.

CHARACTERISTICS OF $^4He^+$ OBSERVED ON DECEMBER 10, 1981

In their systematic search for $^4He^+$ in the solar wind covering the period from 1972 to 1980, Zwickl et al. [1982] have found three distinct events with detectable amounts of $^4He^+$. In figure 1 we show an additional case with enhanced abundance at M/Q = 4.0 which we attribute to an excess of $^4He^+$. This event was seen with the ISEE-3 Plasma Composition Experiment during the night from December 9 to 10, 1981. A first indication of $^4He^+$ was found at 23h of December 9 when the instrument was switched into a mode which covers a M/Q-range from 1.7 to 4.1 after having been in a mode which allows better time resolution but only covers M/Q from 1.7 to 3.0. The event lasted at least until December 10, 2h30m when a data gap of 38 hours began. It cannot be excluded that $^4He^+$ was present in the solar wind for several hours before the instrument was switched to the wider M/Q-range. Indeed, indication for the fact that something unusual was going on, is given by the anomalously large O^{6+}/O^{7+}-ratio which already occurred a few hours before the first detection of $^4He^+$ and lasted throughout the period of observed enhancement of $^4He^+$. However there is no indication for $^4He^+$ before December 9, at 1.00h followed by another data gap.

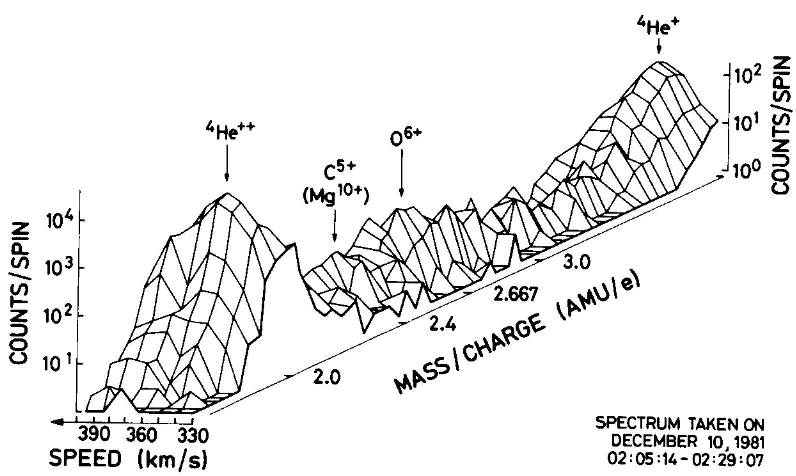

Figure 1: Three dimensional representation of a spectrum taken on December 10, 1981 from 02:05:14 to 02:29:07 UT. $^4He^{++}$, O^{6+}, and $^4He^+$ are visible. The low abundance of O^{7+} indicates that the "freezing-in temperature" of the hot component is $1.2 \cdot 10^6$K or lower.

A sudden increase in solar wind speed and kinetic temperature was observed on December 8, 14.00h. Linking this with the appearance of $^4He^+$, we find that the anomalous enhancement of $^4He^+$ began earlier than 33 hours after the increase in speed but not earlier than 11 hours. It lasted for at least 3 1/2 hours but no longer than 64 hours.

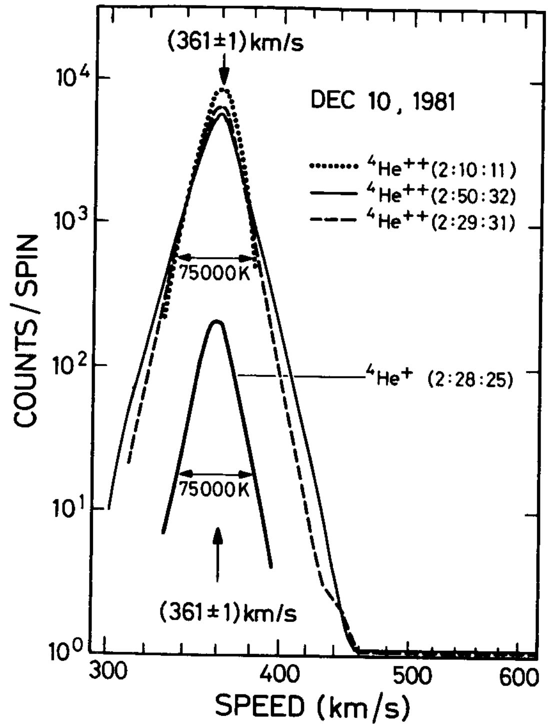

Figure 2: Cross section of the relief in figure 1 in the speed/counts plane at M/Q = 4.0 (lower parabola). For comparison, velocity distributions of $^4He^{++}$ and $^4He^+$ are very similar. The flux ratio is approximately 100.

In figure 2 we show a cross section of the relief of figure 1 taken at M/Q = 4.0 in the count-rate/speed plane. The velocity distribution of $^4He^+$ is compared with the distribution of $^4He^{++}$ shortly before and after the $^4He^+$ profile was taken. Two things can be noted from this comparison.

- The velocity distributions of $^4He^+$ and $^4He^{++}$ do not differ in any respect from each other. Speeds are equal to the narrow limits of uncertainty, the same holds for the kinetic temperature of the two ions.
- The flux ratio of $^4He^{++}$ to $^4He^+$ is approximately 100.

This observation places limits on possible models for the origin of this $^4He^+$-rich event. It shows that $^4He^+$ is so well incorporated into the solar wind that it is indistinguishable in its kinetic behaviour from other minor ions. This can only be true if interaction of $^4He^+$ with the ambient solar wind plasma is sufficiently intensive suggesting that $^4He^+$ has been flowing within the solar wind from the lower parts of the corona.

SIGNATURES OF "MODERATE" MIXTURES

The most prominent signature of "extreme" mixtures in M/Q-spectra is certainly the appearance of $^4He^+$. We will now look for features of plasma mixtures with less extreme temperature differences in their constituents. An example of a M/Q-spectrum produced with an artificial moderate mixture is shown in figure 3. We have mixed 50% isothermal solar wind at $3.0 \cdot 10^6$K ionization temperature with 50% at $1.0 \cdot 10^6$K using the instrument functions of the ISEE-3 Plasma Composition Instrument, chemical abundances from Ross and Aller [1976] and the rates of Shull and van Steenberg [1982] in order to compute the ionic abundances for the simulation. A good fit in the range of the O^{6+}- and O^{7+}-peaks is obtained with an isothermal solar wind at $1.6 \cdot 10^6$K. As can be seen in figure 3, an amazingly good match results. Obviously, if the simulated mixture were treated as observational

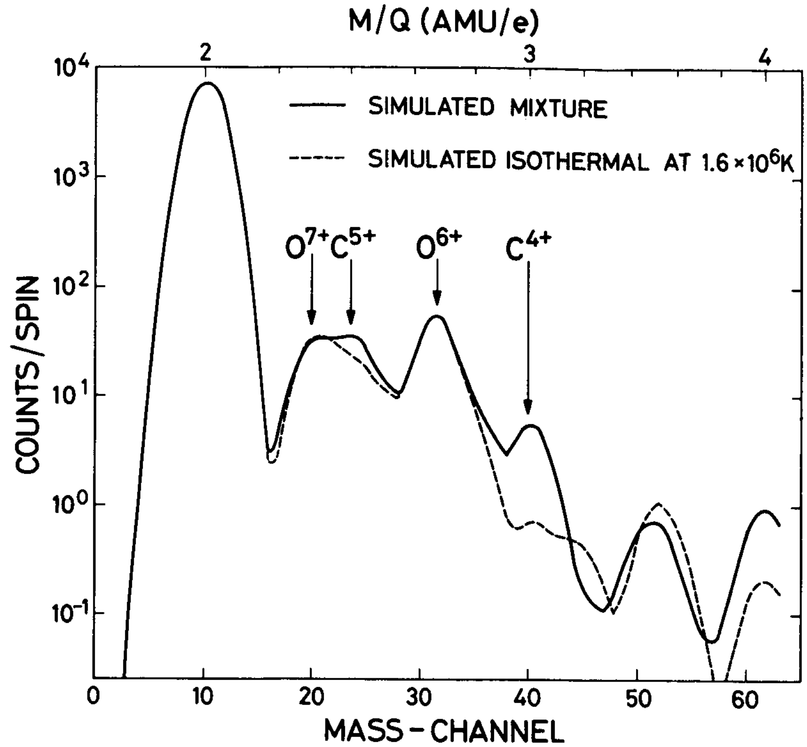

Figure 3: Artificial spectrum produced with a "moderate" plasma mixture. The hot component was $3.0 \cdot 10^6$K, the cool component at $1.0 \cdot 10^6$K. Equal fluxes for both components and the instrument functions of the ISEE-3 plasma composition experiment have been used. The dashed line represents a simulated isothermal spectrum produced with standard chemical abundances. At a temperature of $1.6 \cdot 10^6$K, an optimal fit to the mixture in the oxygen region (mass-channels 17 to 35) is obtained.

data, interpretation as an isothermal plasma would yield such a good approximation that one might be tempted to take it as reality and to proceed to a more refined interpretation basing on wrong assumptions. The most outstanding differences between mixture and isothermal spectrum at $1.6 \cdot 10^6$K is the excess of C^{5+} and C^{4+} in the mixture. This is due to the large ionic abundances of C^{4+} and C^{5+} in the low temperature component at $1.0 \cdot 10^6$K. For normal fluxes, countrates in the C^{4+}-region are only of the order 3 to 5 per spectrum with correspondingly large uncertainties; so the most significant feature remains an excess at M/Q = 2.4 due to C^{5+} for moderate mixtures. Of course, the exact shape of a spectrum composed of different isothermal components depends on the mixing ratios and the temperatures of the components. Nevertheless, in the temperature range from 1 to several million degrees, the dominant peaks next to $^4He^{++}$ will always be O^{6+} and O^{7+}; the next important ingredient will be C^{5+} with a variable size depending on the temperature of the cooler component. This is predominantly due to the relatively large abundance of C in solar material (C/O = 0.6 [Ross and Aller, 1976]).

In the following, we will have to investigate whether excessive flux at M/Q = 2.4 compared to isothermal ion distribution and standard chemical abundances necessarily requires plasma mixing in the corona or whether alternative explanations might be possible.

DEPARTURE FROM ISOTHERMAL EQUILIBRIUM IN THE CORONA

Up to now, we have implicitly assumed that in a given sample of solar wind the state of ionization of elements in the plasma depends only on a given coronal temperature which is equal for all elements. This is certainly only an approximation. As has been shown by Hundhausen et al. [1968] this assumption holds as long as recombination times and ionization times for ions are much shorter than their characteristic travel times within the corona. Bame et al. [1974] have used the observation that several ions of iron and silicon indicate lower freezing-in temperatures than oxygen, for determining thermal gradients in the lower corona. From the fact that heavier ions in general recombine faster, one could hastily conclude that carbon would freeze-in at lower depths than oxygen, thus indicating higher freezing-in temperatures than oxygen. This however neglects that at given temperatures the most abundant ions of different elements have different electronic configurations. At $1.6 \cdot 10^6$K, oxygen is most prominent in the form of the helium-like ion O^{6+} while carbon is already fully ionized to a large extent with a significant rest of H-like C^{5+}. Thus we have to compare ions not only of elements with different masses but, more important, with different electronic configurations. Predictions of the state of ionization of an element, also qualitative ones, can therefore only be made by careful computations based on models of the solar corona. We have used a simplistic model for dependences o electron densities, electron temperatures and ion speeds upon the solar distance and performed an exploratory study for the elements carbon, oxygen, magnesium, silicon, and iron. We have assumed that the electron density decreases with r^{-3}. In order to keep the ion flux per sterad constant, we have assumed $v \sim r$. The last assumption certainly does not hold for larger solar distances, however, we depend on a good agreement of the model with reality in the inner corona, where the charge state of an element is fixed and there this assumption holds to a first approximation. The temperature has been assumed to vary with $r^{-\alpha}$, and computations have been done for a set of four values of α. Ionic abundances at 1 AU have been calculated by solving systems of equations for production and destruction of ions in the range $r = 1\ R_s$ to 1 AU using the above model on depth dependences and the ionization and recombination rates compiled by Shull and van Steenberg [1982].

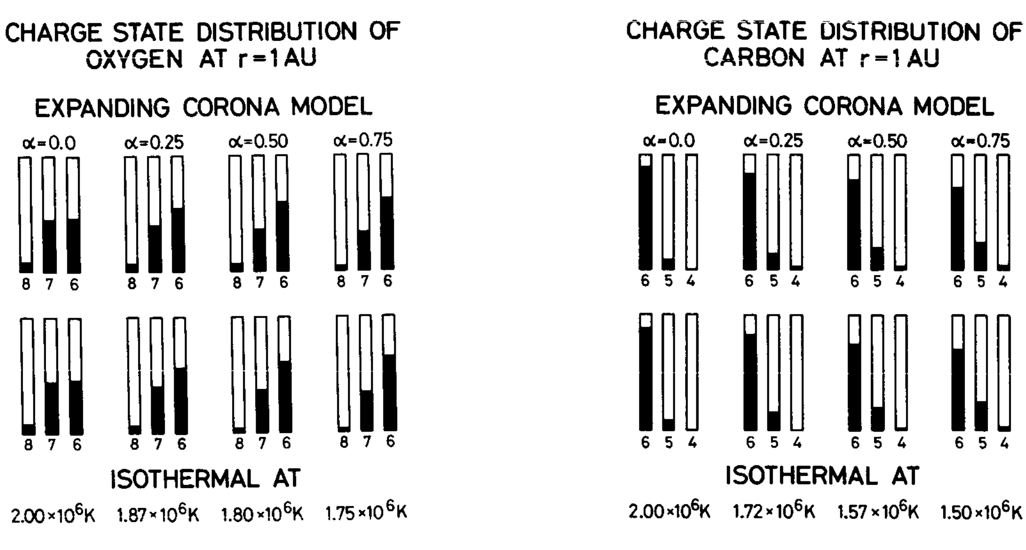

Figure 4: Using an expanding corona model we have calculated the charge state distribution of carbon and oxygen at 1 AU. An initial electron density of 10^9 per cm^3 and an initial electron temperature of $2.0 \cdot 10^6$K was assumed. The density varied with r^{-3}, the temperature with $r^{-\alpha}$, and the speed was assumed to be proportional to r. For comparison, charge state distributions for a static, isothermal corona are shown in the lower row.

Results are depicted for carbon and for oxygen in figure 4. Charge state distributions have been computed for α = 0.25, 0.5 and 0.75, assuming initial distributions as for an isothermal corona at T = 2.0 $\cdot$ 10^6K, the initial electron density was taken to be 1 $\cdot$ $10^9 cm^{-3}$. For comparison we also show charge state distributions for isothermal coronae (α=0) at different temperatures. These temperatures have been chosen in order to give a good approximation of the charge state distribution of the element to the expanding corona model at the respective values for α. Evidently, there is no difference between equilibrium calculations and those for non-equilibrium for carbon and oxygen; however, in the case of carbon, temperatures derived from the isothermal fits are significantly lower than for oxygen. In figure 5 we show the result of similar computations for silicon. This figure illustrates that it is impossible to find satisfying matches to the whole range of charge states of a heavier element such as Si with isothermal models.

Since carbon in general shows lower freezing-in temperatures than oxygen, we expect to find a certain excess of C^{5+} and C^{4+} in spectra obtained from expanding corona models relative to simulations in which all elements have been assumed to have equilibrium charge state distributions at one given temperature. This is shown in figure 6 for two simulated spectra: A small excess is visible at M/Q = 2.4 and also at

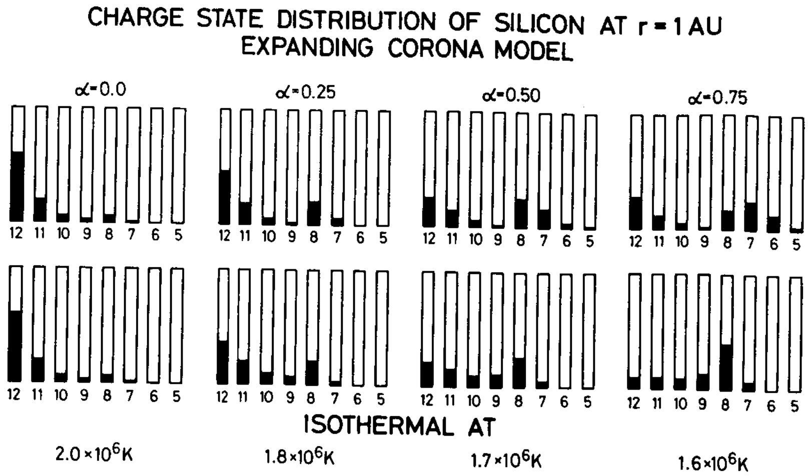

Figure 5: Same as figure 4 but for silicon. Obviously for larger values of α no good isothermal fits exist for this element.

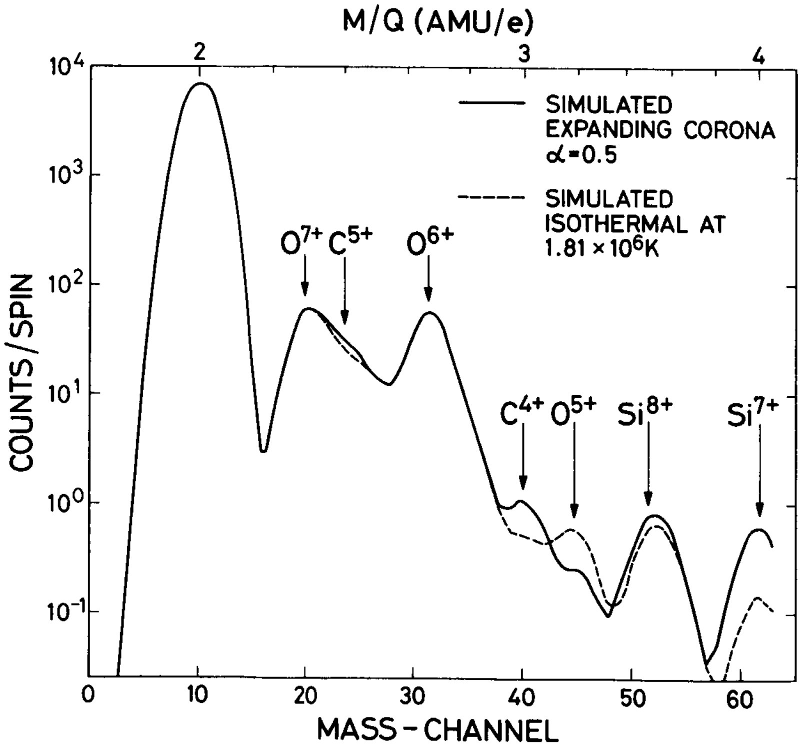

Figure 6: As in figures 4 and 5 we have used an expanding corona model with α = 0.5 and the instrument functions of the ISEE-3 plasma composition instrument in order to simulate the spectrum drawn as a solid line. For comparison, a dashed line indicates an isothermal spectrum which fits the oxygen peaks. Small excess in the C^{5+}- and C^{4+}-peaks are visible.

M/Q = 3.0 for the expanding corona simulation relative to the isothermal model. Although the excess is considerably smaller than in the case of plasma mixing (section 3), in view of the approximate nature of our expanding model we cannot completely exclude the possibility that an excess peak at M/Q = 2.4 might rather be due to departure from equilibrium than to "moderate" plasma mixing.

ANOMALOUS ABUNDANCE OF C AND Mg

It is possible that enhanced chemical abundances of C or Mg could produce anomalous peaks at M/Q = 2.4. A priori C seems to be the more likely candidate for such enhancements. Because of its larger solar surface abundance, an enhancement of carbon by a factor of 3 over normal solar abundance could produce a significant excess at M/Q = 2.4. Correspondingly it requires an enhancement of a factor of 10 to 30 for Mg in order to generate a significant excess. Although these enhancements are much larger than those required for carbon they cannot be excluded. In contrary, it is well known that in the case of silicon, large fluctuation in its relative abundance exist [Bame et al., 1975]. An example of temporary enhancement of Si is given in figure 7 which shows a spectrum obtained with ISEE-3. A fit with normal solar abundances in the oxygen region gives a good match with measured data while a large discrepancy is seen in the Si-region. Silicon seems to be enhanced relative to oxygen by a factor of 30 compared to normal solar abundances [Ross and Aller, 1976].

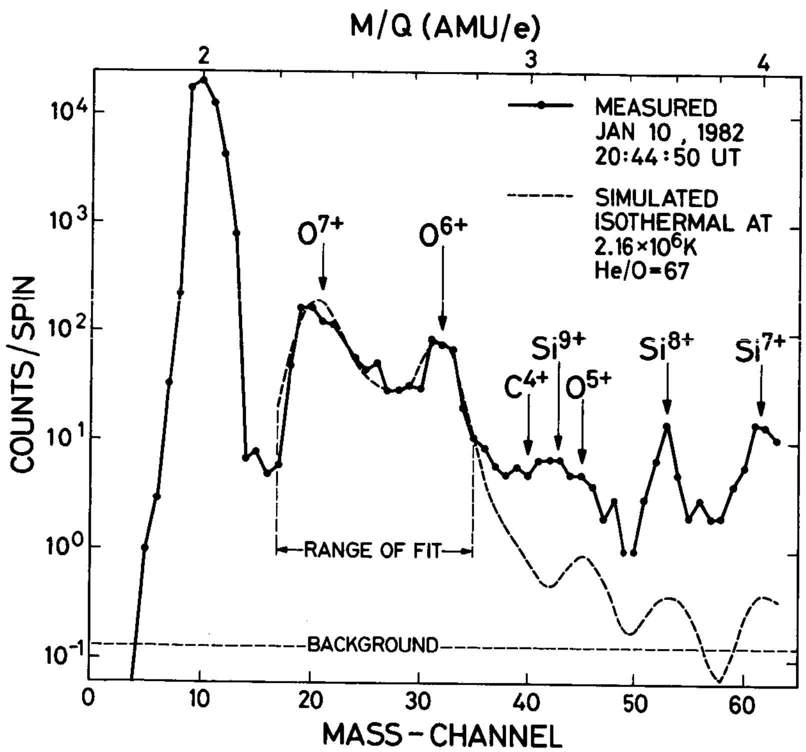

Figure 7: A case of enhanced silicon abundance observed with the ISEE-3 Plasma Composition Experiment on Jan. 10, 1982 (solid line). A good fit (dashed line) is obtained in the oxygen region with standard solar surface abundances, a He/O ratio of 67, and a (isothermal) freezing-in temperature of $2.2 \cdot 10^6$K. The departure in the region of the silicon peaks indicates an enhancement of silicon by a factor of 30.

Geiss [1982] has argued that such fluctuations could be caused by differences in the first ionization potential of different elements. Silicon has a first ionization potential of 8.149 V, far below Ly-α and is therefore one of the most sensitive elements among the major species. This also holds for Mg (7.644 V). Thus, if silicon shows enhanced relative abundance due to incomplete first ionization of the other elements, the same will happen to magnesium. Independent of the model for further ionization and the exact ionization - and recombination rates, Mg^{10+} at M/Q = 2.4 will be a prominent species because of its helium-like electron shell in a wide temperature range. Therefore, we favour enhanced Mg abundances over the possibility of carbon enrichments, if anomalous chemical abundances were the reason for an excess at M/Q = 2.4.

DISCUSSION AND CONCLUSIONS

Kunz et al. [1983] report the observation of anomalous enhancements at M/Q = 2.4 based on measurements by the ISEE-3 Plasma Composition Experiment. In principle, various causes could be responsible for this observation and at present is impossible to definitely conclude in favour of the mixing hypothesis or against it. More developed instruments which allow the detection of charge and mass/charge are required to establish a final conclusion. Meanwhile, we briefly summarize our reasons for not dismissing the mixing hypothesis at once. Although, as pointed out in the introduction, the dynamics of mixture is not understood, cases of increased $^4He^+$ fluxes from the lower corona have been found and there is almost no doubt that these events are caused by incomplete ionization of solar surface material. In order to prevent $^4He^+$ from further ionization by collision with the ambient electrons in the corona, it has to be protected up to a distance of the order of 10 solar radii from the solar surface. Beyond, densities are small enough that $^4He^+$ can survive up to 1 AU. If we assume that a hypothetical magnetic structure has a typical size of 1 R_s and the time required to protect the plasma to be of the order of 10^5 s, a diffusion coefficient acting against the protective structure should be of the order of 10^{17} cm^2/s. Diffusion coefficients of charged particles across magnetic fields can be calculated using the relation

$$D_\perp = D \frac{\nu_c^2}{\omega_c^2} \qquad (1)$$

[e.g. Krall and Trivelpiece, 1973] with ν_c collision frequency, ω_c cyclotron frequency and D diffusion coefficient of neutral particles.

We find

$$D_\perp \approx 10^{14} \frac{n_9 \ln \Lambda}{B^2 [nT]} \cdot \sqrt{\frac{A}{T_6}} \qquad (2)$$

T_6 : Temperature in 10^6K,

n_9 : density in 10^9 cm^{-3},

B : magnetic field in nT,

Λ : ratio of Debye length to impact parameter.

This is a very coarse estimate which will only give the order of magnitude. In any case, we can see that magnetic bottles built of fields of the order of a few nT and sizes of 1 R_{solar} will prevent mixture by plasma diffusion for days. From dimensional considerations it seems probable that there is no strong change in diffusion times with distance from the solar surface r: If the size of a magnetic structure increases with r, the electron density decreases with r^{-3}, and if the magnetic fields decrease with r^{-2}, we find that the diffusion time, i.e. the characteristic time until a certain fraction of plasma has diffused into the magnetic structure, increases with r. Obviously, mixture by plasma diffusion is only a lower limit to possible transport of cool and hot plasma into each other, distortion of magnetic structures might lead to a much more efficient, turbulent mixture. In fact, since we obtain highly ionized plasma and $^4He^+$ together at 1 AU, the two components have to be mixed to a scale smaller than 1000 km. Note, that in expression (2), $D \sim T^{-1/2}$, i.e. the higher the temperature of the plasma the easier it is to separate it from other components by magnetic fields. It is certainly not more difficult to produce "moderate" mixtures than extreme ones. Raymond and Foukal [1982] have presented evidence that departure from thermal equilibrium is a common phenomenon in coronal loops, thus one would not be amazed to find plasma mixtures emanating regularly from magnetically active regions. We conclude that the appearance of some peaks in M/Q-spectra unexpected in isothermal plasma can be interpreted in terms of an expanding corona model with freezing-in occurring at different levels, hence serving as a diagnostic tool for the depth structure of the corona [Bame et al., 1974]. Alternatively in cases of more complicated magnetic field configurations, e.g. near sector boundaries, M/Q-spectra might have to be interpreted as mixtures of plasma of different freezing-in temperatures and ultimately serve as a diagnostic tool of lateral structures of the corona near the solar surface.

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