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Solar coronal acceleration and its astrophysical implications.

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Abstract. Selective energization of minority coronal ions in impulsive flares serves as an important tool to delineate relevant physical mechanisms which operate in the solar corona. Inclusion of these processes into the more intense long-duration acceleration by interplanetary shocks gives a new heliospheric baseline abundances of minority elements during active periods. It is suggested that a similar process may explain the enrichment of minority elements in planetary nebulae, solving partly the "astrophysical ^{3}He problem", with important implications for galactic evolution and cosmology.

1 Introduction

Solar energetic ions with energies of 0.01-10.0 MeV/nucleon are frequently observed in the interplanetary space. They carry important information about physical processes in the solar corona and in the heliosphere, and by implication in other astrophysical sites. Their abundances and isotopic states are often distinctly different from the coronal or solar wind values. The relative abundance of such ions helps our understanding of the intense physical phenomena which occur at the Sun and of their heliospheric effects. By analogy, these processes may help in understanding the observed abundances in other astrophysical regions which are affected by a single, magnetically active, central stellar object. Spectroscopy is the best method for measuring astrophysical abundances, but *in situ* heliospheric observations are indispensable in discerning several possible physical processes which affect astronomical objects.

It is generally believed that the processes which accelerate the Solar Energetic Particles (SEP) are initialized due to relaxation of stressed coronal magnetic field configuration. In the recent years a generally accepted paradigm makes a distinction between the "gradual" events which may last for several days and which are the source of energetic particles accelerated by interplanetary, fast shocks due to Coronal Mass Ejections, and "impulsive" events with duration of a fraction of a day or less, which generate energetic particles via wave-particle interaction on the coronal field lines. Large, gradual SEP events are believed to involve inhomogeneously self-generated waves and scattering of particles back to the propagating shock [Lee, 1983], with a transport to the observing location [Reames and Ng, 1998]. Some temporal and systematic variations in element abundances can be attributed to this scattering; the observed variations depend on the charge-to-mass ratio and on the generated wave spectrum, which is determined by the injected particle spectrum, i.e. shock strength. Besides these variations, the resulting energetic ions have relative abundances and ionization states similar to the corona [Luhn *et al.*, 1985]. Smaller, impulsive SEP events involve selective enrichment of a subset of coronal ions satisfying resonance conditions with electromagnetic waves which propagate along the coronal field lines due to a flare reconfiguration of a strongly stressed magnetic field; as a result one observes a dramatic abundance enhancement by factor of 10^3-10^5 in the isotopic ratio of ^{3}He/^{4}He [Hsieh and Simpson, 1970; Mason *et al.*, 2000]. Flares enriched in ^{3}He are correlated with smaller enrichments by factor 3-10 (with respect to O) in heavier ions up through Fe [Mason *et al.*, 1986; Reames *et al.*, 1994] and possibly with large enrichments by factor 100, 1000, in the heavy trans-iron elements with $34 < Z < 40$, $50 < Z < 56$, respectively (Reames *et al.*, 2000). It should be noted that the coronal abundances ratio of the trans-iron elements, relative to Fe, satisfy $\sim 10^{-5}$, hence, until recently most of the heavy ion measurements were focused around Fe.

We assess the relation between these enhancements in impulsive flares through an analysis of the interaction with waves on the coronal field lines, and apply the results to astrophysical spectroscopic measurements at planetary nebulae.

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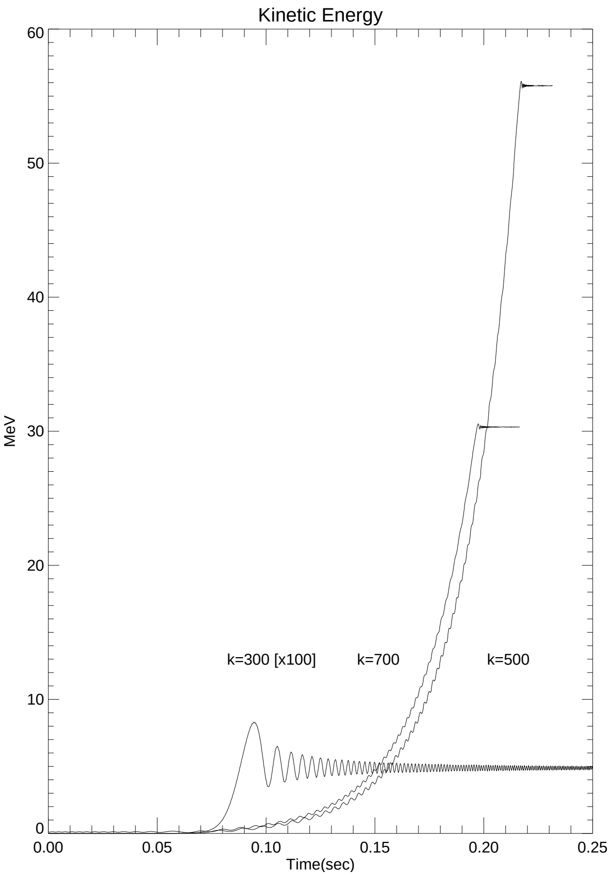

Fig. 1. Energization of Fe ions interacting with different perpendicular wavenumbers: k= 300 km^{-1} (plot enhanced by a factor of 100), k= 700 km^{-1} and k= 500 km^{-1}; B = 500 G, n=10$^9 cm^{-3}$.

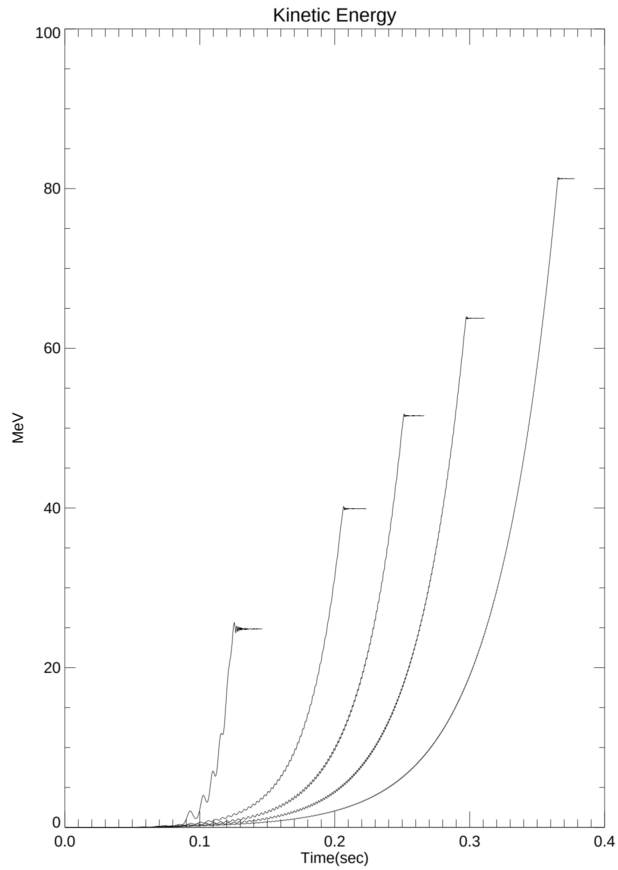

Fig. 2. Energization of Fe ions with varying coronal charge states: Z= 16, 18, 20, 22, 24 (from left to right), A=56; B = 500G, n=10$^9 cm^{-3}$.

2 Enhancement of Minority Ions in the Solar Corona

The different measurements related to the presence of accelerated electrons in impulsive solar flares and in the planetary terrestrial aurora may make the physics of solar flares analogous to that of the earth's aurora. Both environments consist of very low β plasmas, are dominated by two majority species and, as a result of magnetic field reconfigurations, are subjected to intense electron fluxes. In the corona these electron fluxes are deduced from the bremsstrahlung X-ray emissions, while in the aurora they can be measured directly by rockets or satellites.

The acceleration model is based on the resonant interaction with the propagating electromagnetic cyclotron waves [e.g., Roth and Temerin, 1997]. The frequency range of these waves is confined to below the hydrogen gyrofrequency Ω_H and above the ion-hybrid frequency. ^{3}He ions are unique among all the minority coronal ions in possessing a cyclotron frequency in that frequency range. When the wave propagates along the inhomogeneous magnetic field and passes through Doppler-shifted gyrofrequency of ^{3}He, these ions are resonantly accelerated. The waves are damped near the H and ^{4}He gyrofrequencies; therefore ions with a charge-to-mass ratio of 0.5 Ω_H, like ^{4}He or fully ionized main isotopes of CNO, are not significantly affected by the waves. On the other hand, those ions which are not fully ionized in the coronal temperatures and exist in various charge states, like Fe, Mg, Si, and trans-iron elements, may be accelerated when the resonance condition with a higher harmonic of their cyclotron frequency is satisfied. This mechanism can also accelerate selective isotopes; it was suggested that impulsive flares can enhance the isotopic ratio ^{22}Ne/^{20}Ne [Temerin and Roth, 1992]; similarly, one may expect an increase in the isotopic ratio ^{13}C/^{12}C, which is important in the evolution of low-mass red giant stars.

Recent Advanced Composition Explorer (ACE) observations point out to an existence of a subset of ^{3}He impulsive events in which both ^{3}He and Fe exhibit similar energy distribution form, peaking in rigidity around 40-50 MV (200-400keV/n and 100keV/n, respectively). This similar shape, which differs from all other observed ions spectra, indicates a commonality in their acceleration mechanism. Additionally, the velocity spectrograms of the observed ions show that ^{3}He and Fe arrive along the same energy-time curves, confirming a simultaneous injection at the sun [Mason *et al.*, 2000]. Recent study of 45 ^{3}He-rich events concluded that ^{3}He /^{4}He and

Fe/O enhancements are clearly correlated [Ho *et al.*, 2000].

Although the resonant processes which accelerate ^{3}He and a subset of heavy ions (mainly Fe) are similar, there exist several reasons for the much less effective energization of Fe isotopes. While ^{3}He resonates with the lowest harmonic of the waves (n=1), Fe and other heavy ions require higher harmonics, n= 2, 3 ... [Roth and Temerin, 1997]; therefore the initial heavy-ion gyroradius must be a non-negligible fraction of the perpendicular wavelength and only the tail of the distribution can be affected by the interaction. Second, heavy ions with velocities smaller than ^{3}He ions of the same energy, may be removed out of resonance through Coulomb scattering. Third, not all the various charge states of the coronal heavy elements may simultaneously satisfy the resonance conditions. Therefore, although the acceleration mechanisms between ^{3}He and Fe are similar, there is only a tenuous quantitative connection between their enrichments in each flare.

Figure 1 shows the time history of three Fe ions interacting along the coronal field lines with monochromatic waves of varying perpendicular wavenumbers. One observes optimum wave properties for maximum energization. For $k_\perp \rho$ too small, ($\rho = v_\perp/\Omega$ denoting the gyroradius) the interaction is weak due to the small value of the Bessel function J($k_\perp$ ρ) before the ion is ejected from the interaction region by the mirror force. For $k_\perp$ too large the maximum energization decreases since it satisfies approximately $\rho \sim \nu/k_\perp$, where ν is the root of the Bessel function. Figure 2 shows the time history of Fe ions with different q/m ratios, taken from coronal distribution with varying charge states: Z= 16-24, and A=56. The frequencies of the waves are adjusted accordingly to allow resonant interaction. We observe that for a given wavenumber the final energy increases with q/m, or equivalently with the gyrofrequency. Hence, higher charge states are more energized, provided they can satisfy the resonant condition.

Generally, the wave spectrum determines the energy spectrum of the interacting ions. If the same mechanism affects ^{3}He and Fe ions, and Fe energization is not quenched by the above mentioned hindrances, the maximum energy of both ions is determined by the lowest wavenumbers with a sufficient power, k_o, and are related by an energy/nucleon ratio $[(\nu_1/\nu_2)(\Omega_{He}/\Omega_{Fe})]^2 \sim 4(\nu_1/\nu_2)^2$, i.e. of the same order.

3 Abundances of Minority Ions in Planetary Nebulae

Tracing the history of each one of the light isotopes which were formed in the big bang nucleosynthesis (BBN) is crucial for an understanding of the early Universe. Chemical galactic evolution and precise present-day measurements of the light isotopes can be used to set bounds on the BBN models. ^{3}He is one of the main elements that can be used as a cosmological ”baryometer”, and understanding its evolution is paramount in constraining the baryon-to-photon ratio [e.g., Yang *et al.*, 1984]. Lack of consistency between abundance observations and galactic evolutionary models poses a major problem for the cosmological theory. The presently observed ^{3}He abundance is not much higher than the BBN yield, i.e. the galactic evolution does not allow for a significant increase of ^{3}He. However, in the standard models of stellar evolution on the main sequence [Iben, 1967; Truran and Cameron, 1971] ^{3}He peak builds up for low-mass stars due to p-p reactions, while ^{3}He is destroyed in higher mass stars where the CNO cycle dominates the hydrogen burning. The enhanced ^{3}He which is embedded in the convective layers during the first dredge-up on the red giant branch (RGB) cannot be destroyed because of the insufficiently high temperatures in these regions, and is finally ejected into the interstellar medium. Therefore, for a generally accepted mass function, the abundance of ^{3}He should increase in time and be higher in the regions of stronger stellar processing (closer to the galactic center). The observations do not confirm these conclusions, placing constrains on models of chemical galactic evolution.

The abundance of ^{3}He can be determined beyond the local solar neighbourhood only via measurements of the 3.46 cm (8.665 GHz) hyperfine transition of ^{3}He$^+$. H II regions and planetary nebulae (PN) are the main observable sources of this transition [e.g., Bania *et al.*, 1997]. ^{3}He measurements in the protosolar material [Geiss, 1993], the local interstellar medium [Gloeckler and Geiss, 1996] and galactic H II regions [Balser *et al.*, 1999a] indicate that the ^{3}He/H abundance ratio is similar to the non-processsed galactic value of $\sim 2 \times 10^{-5}$. However, in a series of very long observations [Balser *et al.*, 1997; 1999b] several PN sources were detected with ^{3}He/H = $10^{-4} - 10^{-3}$, i.e. more than an order of magnitude larger than those found in any H II region, local interstellar medium or protosolar system. The high ^{3}He/H poses an important question with respect to the galactic evolution of the light elements. The disagreement between the observed abundances of ^{3}He throughout the Galaxy and the chemical evolution models, together with observations of ^{3}He enhancement around PN was termed the ”^{3}He problem” [Galli *et al.*, 1995], which has stimulated studies of many non-standard models for both stellar and galactic chemical evolution. The main thesis involved modification of the stellar evolution due to additional chemical mixing in specific evolutionary stages. The observed anomaly in the isotopic ^{12}C/^{13}C ratio in a number of evolved stars, which was shown to be below the standard models (5 vs 30) for masses $< 2M_s$, was suggested as an indicator for a non-standard mixing after the first dredge-up before the end of RGB phase (Hogan, 1995), with a similar destruction of ^{3}He (Charbonnel, 1995). This scenario would require that the PN mass progenitors have masses $> 2M_s$, however new analysis of the relevant PN showed that their masses satisfy 1.2 $M_s < M < 2.2M_s$ [Galli *et al.*, 1997]. Therefore the consistency with presolar and local ISM values is possible if most of the low-mass stars have undergone enhanced ^{3}He depletion (Charbonnel and Nascimento, 1998), and then the solution of the observed enhanced ^{3}He abundances in PN must be related to a different physical process. Resonant acceleration in planetary nebula may contribute significantly to the observed abundances of He, and possibly C isotopes.

Measurements on the WIND satellite show enhancements in the $^3He/^4He$ (or equivalently $^3He/H$) ratio in the range from MeV/nucleon all the way down to tens of keV/nucleon [Reames *et al.*, 1997]. More interestingly, the $^3He/^4He$ enhancements have been observed in gradual events lasting several days, when the isotopic He ratio has increased by a factor of five or more above the solar value [Mason *et al.*, 1999]. Similar study regarding $^{22}Ne/^{20}Ne$ finds this ratio enhanced vs the solar wind by a factor of 1.6 [Leske *et al.*, 1999]. The limited statistical study of the correlation between enhanced $^3He/^4He$ and Fe/O in impulsive events which are embedded in gradual events indicates a positive correlation between both ratios, similarly to observations of isolated impulsive events; additionally, through direct ionization measurements an increased Fe charge states are observed. Therefore, the impulsive events which are embedded into the gradual events and which are able to enhance $^3He/^4He$ by several orders of magnitude, increase the baseline (average) heliospheric $^3He/^4He$. Although the impulsive events last over relatively short period of time, their frequent appearance during the active solar periods increases the abundance of ^3He in the interplanetary medium. It is suggested, that in addition to the specific requirements from the stellar evolution [Rood *et al.*, 1976; Olive *et al.*, 1995] to produce ^3He in low-mass stars in PN and deplete it in H II regions, as required for consistency with observations, one may consider a planetary nebula with its very hot central star and very intense magnetic activity as a source of steady enhancement of ^3He over a broad range of energies. The resulting mixing of the He isotopes results in an average higher value of $^3He/^4He$ and $^3He/H$ in the surrounding environment. The large H II regions which consist of many stars with on the average much less intense magnetic activity will not reach such high baseline values.

Several future tests may be of interest to delineate the relevant physical processes which control the abundances of the minor elements in planetary nebulae. Analyses implementing nuclear physics process require a non-standard deep mixing mechanism in order to lower the isotopic C ratio and deplete ^3He. In this scenario, enhanced abundances of ^3He in some of the observed PNs fall into a category of events which did not undergo mixing. On the other hand, plasma physics processes are able to enrich ^3He in the PN via mechanism that can be confirmed by heliospheric *in situ* observations. The $^3He/^4He$ isotopic enhancement is weakly correlated to the isotopic $^{12}C/^{13}C$ decrease. ^{13}C with lower gyrofrequency can resonate with part of the electromagnetic spectrum, in contrast to ^{12}C, but the C isotopic change is expected to be small. Latest spectroscopic measurements of isotopic correlation between ^3He and ^{13}C is inconclusive [Palla *et al.*,, 2000]. In this context, the main observational correlation with enhanced ^3He should focus on Fe, provided it can be measured spectroscopically.

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References

Balser, D. S., Bania, T. M., Rood, R. T., and Wilson, T. L., *Astrophys. J.*, **483**, 320, 1997.

Balser, D. S., Bania, T. M., Rood, R. T., and Wilson, T. L., *Astrophys. J.*, **510**, 759, 1999a.

Balser D. S., Rood R. T., and Bania T. M., *Astrophys. J. (Lett.)*, **522**, L73, 1999b.

Bania, T. M., Balser, D. S., Rood, R. T., and Wilson, T. L., *Astrophys. J. Supp.*, **113**, 353, 1997.

Charbonnel, C., *Astrophys. J. (Lett.)*, **453**, L41, 1995.

Charbonnel, C. and Nascimento, J. D., *Astron. Astrophys.*, **336**, 915, 1998.

Galli, D., Stanghellini L., Tossi M., and Palla, F., *Astrophys. J.*, **443**, 536, 1995.

Galli, D., Stanghellini L., Tossi M., and Palla, F., *Astrophys. J.*, **477**, 218, 1997.

Geiss, J., in *Origin and Evolution of the Elements*, ed. N. Prantzos, E. Vangioni-Flam and M. Casse, (Cambridge: Cambridge University Press), 1993.

Gloeckler, G. and Geiss, J., *Nature*, **381**, 210, 1996.

Ho, G.C., in *Acceleration and Transport of Energetic Particles Observed in the Heliosphere*, p.99, ACE-2000 Symposium, Indian Wells, California, AIP Conf. Proc., Vol. 528, 2000.

Hogan, C. J.,*Astrophys. J. (Lett.)*, **441**, L17, 1995.

Hsieh, K. C. and Simpson, J. A. *Astrophys. J. (Lett.)*, **162**, L191, 1970.

Iben, I., *Astrophys. J.*, **147**, 624, 1967.

Lee, K. A., *J. Geophys. Res.*, **88**, 6109, 1983.

Leske, R. A., Mewaldt, R. A., Cohen, C. M. S., Cummings, A. C., Stone, E. C., Wiedenbeck, M. E., Christian, E. R., von Rosenvinge, T. T. *Geophys. Res. Lett.*, **26**, 2693, 1999.

Luhn, A., Klecker, B., Hovestadt, D., and Möbius, E., *Astrophys. J.*, **317**, 951, 1987.

Mason, G. M., Reames, D. V., Klecker, B., Hovestadt, D., and von Rosenvinge, T. T., *Astrophys. J.*, **303**, 849, 1986.

Mason, G. M., Mazur, J. E, and Dwyer, J. R., *Astrophys. J. (Lett.)*, **525**, L133, 1999.

Mason, G. M., Dwyer, J. R. and Mazur, J. E., *Astrophys. J. (Lett.)*, **545**, L157, 2000.

Palla, F, R Bachiller, Galli, D., Stanghellini L., Tossi M., and Galli, D., *Astron. Astrophys.*, **255**, 69, 2000.

Olive, K. A., Rood, R. T., Schramm D. N., and Vangioni-Flam E., *Astrophys. J.* , **444**, 680, 1995.

Reames, D. V., von Rosenvinge, T. T., and Lin, R. P., *Astrophys. J.*, **292**, 716, 1985.

Reames, D. V., Meyer, J. P., and von Rosevinge, T. T., *Astrophys. J. Supp.*, **90**, 649, 1994.

Reames, D. V., Barbier, L. M., von Rosenvinge, T. T., Mason, G. M., Mazur, J. E., and Dwyer, J. R., *Astrophys. J.*, **483**, 515, 1997.

Reames, D. V., and Ng, C. K., *Astrophys. J.*, **504**, 1002 , 1998.

Reames, D. V., *Astrophys. J. Lett.)*, **540**, L111, 2000.

Rood, R. T., Steigman D. G., and Tinsley, B. M., *Astrophys. J.*, **207**, L57, 1976.

Roth, I. and Temerin, M., *Astrophys. J.*, **477**, 940, 1997.

Temerin, M., and Roth, I., *Astrophys. J. (Lett.)* , **391**, L105, 1992.

Truran, J. W., and Cameron, A. G. W., *Astrophys. J. Supp.*, **14**, 179, 1971.

Yang J., Turner M. S., Steigman, G., Schramm, D. N., and Olive K. A., *Astrophys. J.*, **281**, 493, 1984.