



## The P, S, Ar, and Ca isotopic composition of the galactic cosmic ray source

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**Abstract:** Galactic cosmic ray (GCR) measurements of the phosphorus, sulfur, argon, and calcium isotopes made by the Cosmic Ray Isotope Spectrometer (CRIS) aboard NASA's *Advanced Composition Explorer* are reported over the energy range from  $\sim 100$  to  $\sim 400$  MeV/nucleon. The propagation of cosmic rays through the Galaxy and heliosphere is modeled to determine isotopic source abundance ratios  $^{31}\text{P}/^{32}\text{S}$ ,  $^{34}\text{S}/^{32}\text{S}$ ,  $^{38}\text{Ar}/^{36}\text{Ar}$ , and  $^{36}\text{Ar}/^{40}\text{Ca}$ . By deriving the GCR source abundance of argon (a noble gas) and calcium (a refractory), it is determined that material in grains is accelerated to GCR energies a factor of  $\sim 6.4$  more efficiently than gas-phase material in this charge range. With this information, the interstellar dust fraction of phosphorus and sulfur at the cosmic ray source is shown to be consistent with astronomical measurements of hot galactic environments.

## Introduction

Volatile elements, those that do not readily condense into grains, in the galactic cosmic rays (GCRs) are significantly depleted at their source compared to the solar system [1, 2]. The proposed mechanism for this fractionation is the sputtering of GCR seed material off of high-velocity refractory grains through collisions with ambient gas in the GCR acceleration environment [3], resulting in the preferential acceleration of grain condensates over gaseous material. In addition, first ionization potential (FIP) is inversely correlated with condensation temperature for most elements seen in the GCRs. Therefore, the observed GCR fractionation could be controlled by FIP, as was first thought [4], instead of an element's propensity for condensing into grains.

Phosphorus and sulfur have similar FIPs ( $\sim 11$  eV), but S condenses at  $\sim 650$  K and is considered a volatile, where moderately-volatile P condenses at  $\sim 1250$  K. If the GCR fractionation is controlled by volatility rather than FIP, the  $^{31}\text{P}/^{32}\text{S}$  ratio traced

back to the GCR source should be larger than what is measured in the solar system.

The acceleration site of GCRs is likely to be the hot, tenuous cores of superbubbles produced by OB associations where the ambient gas is fully ionized [5]. Dust grains and gas from the interstellar medium mix with stellar ejecta (core-collapse supernovae ejecta and wind material from Wolf-Rayet stars) in the superbubble. Supernova shocks accelerate the mixture of older ISM material and freshly-synthesized ejecta to galactic cosmic ray energies. By determining the source isotopic composition of neon isotopes, the mixture of material inside superbubbles has been estimated to be about 20% stellar ejecta and about 80% material from the surrounding ISM [6, 7]. This amount of mixing was found to be approximately consistent with the source abundances of several refractory elements in the GCRs [8], and is assumed to be consistent with the isotopes of P, S, Ar, and Ca considered in this work.

If material in grains is more efficiently accelerated to GCR energies in the superbubble, the enhance-

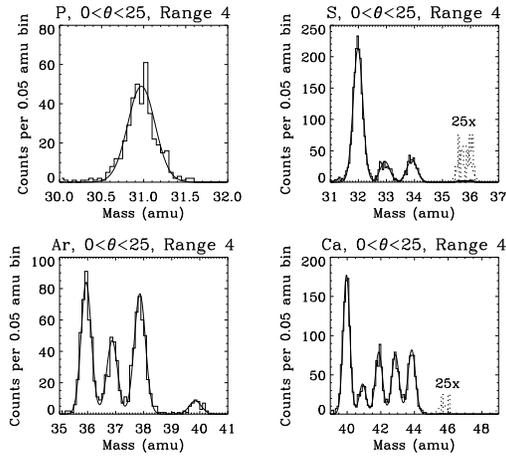


Figure 1: CRIS Range 4 mass histograms for P (201 MeV/nuc median energy), S (211 MeV/nuc), Ar (224 MeV/nuc), and Ca (236 MeV/nuc) with trajectories less than  $25^\circ$ . The solid line is a maximum likelihood fit to the data, from which the relative isotopic abundances are determined.

ment of grains to dust can be measured by determining the source ratio of a purely gas phase species to an element that only exists in grains. Argon is a noble gas that will not condense into grains. Calcium is known to be almost completely depleted out of the interstellar medium onto dust grains [9, 10]. The GCR source  $^{36}\text{Ar}/^{40}\text{Ca}$  ratio is therefore a good measure of the enhancement of dust-condensed material compared to gas in the cosmic ray source. With this grain enhancement factor, it is possible to constrain the interstellar grain/gas composition of P and S in the GCRs.

## Observations

The CRIS instrument aboard *ACE* [11] measures the elemental and isotopic composition of galactic cosmic rays from  $\sim 100$  to  $\sim 400$  MeV/nucleon by making multiple measurements of a particle's  $dE/dx$  and its total energy. The CRIS measurements used in this work were obtained between August 28th, 1997 and August 17th, 1999, a period of solar minimum. The isotopes of P, S, Ar, and Ca are easily resolved in the data set, as shown in the mass histograms in Figure 1.

Isotope ratios of these four elements as observed by CRIS at Earth were determined for each of the seven detector ranges, and from these ratios and publicly-available elemental spectra [12], isotope spectra were calculated.

## Source abundances

Source abundances of the P, S, Ar, and Ca isotopes were derived using GCR species produced purely by spallation during galactic propagation as tracers of the secondary propagation of partially-primary isotopes [13]. The isotopes  $^{33}\text{S}$ ,  $^{36}\text{S}$ ,  $^{42}\text{Ca}$ , and  $^{43}\text{Ca}$  are much more abundant in the GCRs observed by CRIS than what is produced in supernovae [14] or seen in the solar system [15], and so these isotopes will be used to trace the secondary production of the partially-primary isotopes  $^{32}\text{S}$ ,  $^{34}\text{S}$ ,  $^{36}\text{Ar}$ ,  $^{38}\text{Ar}$ , and  $^{40}\text{Ca}$ , which have similar spallation parentage.

A steady-state leaky-box propagation model [16, 17] is employed to derive GCR interstellar spectra. A large data set of direct cross-section measurements was used in concert with the semi-empirical cross-section formulas of Webber [18] to model spallation. For a given isotope, the interstellar spectra of all spallation parents are calculated, then the spectra are modulated using a spherically-symmetric Fisk model. These spectra may not necessarily match the CRIS observations due to uncertainties in the spallation cross sections, so the modeled parent spectra are scaled to match the observations before the model is run again for the isotope of interest. This effectively eliminates the need to know spallation cross sections for all reactions except those that generate the given isotope.

The free parameters of the tracer leaky-box calculation are the source abundance of the two isotopes of interest and the escape mean free path,  $\Lambda_{esc}$ . A larger  $\Lambda_{esc}$  means the cosmic rays have traversed through more material and thus more primary particles have fragmented into lighter secondaries. In this manner, the spectra of the tracer isotopes determines  $\Lambda_{esc}$ . The determination of source abundances can be thought of as a minimization problem, where the quantity to be minimized is a  $\chi^2$  between the leaky-box modeled, solar modulated spectra and the CRIS observations, with the  $\sigma$  values being a quadrature sum of uncertainties in the

| Ratio                           | GCRS               | GALPROP |       | Solar  |
|---------------------------------|--------------------|---------|-------|--------|
|                                 |                    | DR      | PD    |        |
| $^{31}\text{P}/^{32}\text{S}$   | $0.0463\pm 0.0064$ | 0.047   | 0.047 | 0.0198 |
| $^{34}\text{S}/^{32}\text{S}$   | $0.0394\pm 0.0054$ | 0.038   | 0.035 | 0.0444 |
| $^{38}\text{Ar}/^{36}\text{Ar}$ | $0.1570\pm 0.0420$ | 0.065   | 0.049 | 0.1818 |
| $^{36}\text{Ar}/^{40}\text{Ca}$ | $0.224\pm 0.009$   | 0.192   | 0.184 | 1.422  |

Table 1: GCR Source ratios calculated in this work (GCRS), compared to GALPROP ratios derived for diffusion reacceleration (DR) and plain diffusion (PD) with the Solar System ratio for reference [15].

modeled spectra (due to uncertainties in the spallation cross sections) and uncertainties in the CRIS measurements.

The source abundance of each isotope will have an optimal value at the minimum  $\chi^2$ , and the  $1\sigma$  uncertainty will be at minimum  $\chi^2+1$ . Correlated uncertainties exist between the source abundance and the escape mean free path  $\Lambda_{esc}$ , so  $1\sigma$  error ellipses are computed to determine the maximal correlated error between these two parameters. Galactic cosmic ray source ratios were also calculated recently using GALPROP [19], a physically realistic model of galactic cosmic ray propagation. The galactic cosmic ray source abundance ratios for this work and GALPROP, using two different models of GCR diffusion, are given in Table 1, with the solar system ratios for reference.

## Discussion

### FIP and volatility

The derived  $^{31}\text{P}/^{32}\text{S}$  GCR source ratio of  $0.0463\pm 0.0064$  is a factor of  $2.34\pm 0.34$  larger than the solar system value. This enhancement could be a result of preferential acceleration of the moderately-volatile P over the volatile S, or it could be due to a larger amount of P in the GCR source environment.

The GCR source environment is taken to be the cores of superbubbles consisting of a mixture of 80% ISM material and 20% freshly-synthesized ejecta. Most of the ejecta P, S, Ar, and Ca comes from the OB stars exploding as Type II supernovae, with small contributions from other core-collapse explosions of Type Ib/c, Wolf-Rayet winds, and Type Ia supernovae that happen to explode in the superbubble core. The time-averaged mass frac-

tion of a given isotope in the superbubble core, weighted by supernova activity, is calculated based on the formalism of Lingenfelter & Higdon [8].

The superbubble  $^{31}\text{P}/^{32}\text{S}$  ratio is calculated to be 0.0246, or  $\sim 1.24$  times the solar system ratio. The GCR source  $^{31}\text{P}/^{32}\text{S}$  enhancement factor of  $2.34\pm 0.34$  is not reflective of an anomalous source composition, but instead must be due to an increased efficiency in the acceleration of moderately-volatile  $^{31}\text{P}$  compared to volatile  $^{32}\text{S}$ . S and P break the FIP-volatility correlation as mentioned earlier, so this enhancement in  $^{31}\text{P}$  over  $^{32}\text{S}$  lends support to volatility as the controlling parameter in fractionation of the galactic cosmic rays.

### Grain/dust acceleration efficiency

The acceleration efficiency of dust-forming refractory GCR species compared to volatile gas-phase species can be determined by the  $^{36}\text{Ar}/^{40}\text{Ca}$  ratio at the GCR source. In the superbubble core, the  $^{36}\text{Ar}/^{40}\text{Ca}$  ratio is calculated as was done earlier for  $^{31}\text{P}/^{32}\text{S}$ , and is found to be 1.46, which is close to the solar system ratio of 1.42. Therefore, the excess in the GCR source ratio can be attributed to the increased acceleration efficiency for dust grains. The GCR source  $^{36}\text{Ar}/^{40}\text{Ca}$  ratio is  $0.224\pm 0.009$ , which is a factor of  $\sim 6.4$  smaller than the solar system ratio. This is the grain/gas efficiency factor that will be used in the following calculations.

### S and P condensates in the ISM

Grain-condensed S and P in the superbubble core will be accelerated more efficiently to GCR energies, by a factor of 6.4, than gaseous material. The ejecta grain condensation of both of these elements is assumed to be zero based on recent studies of refractory dust condensation of SN 1987A [20]. The free parameters that will be investigated are the S and P grain fraction of the interstellar material that makes up 80% of the GCR seed material. Interstellar sulfur is thought to exist solely in the gas phase in the diffuse interstellar medium [21]. It has been historically assumed to be almost entirely depleted out of the gas phase onto dust grains in molecular clouds [22]. However, arguments have been made against large S depletions in molecular clouds due to the absence of strong IR features from sulfur-

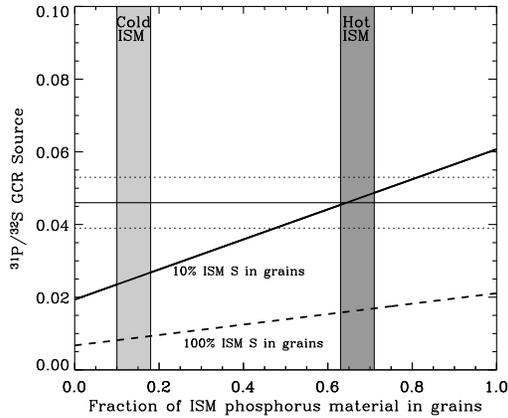


Figure 2: The superbubble  $^{31}\text{P}/^{32}\text{S}$  ratio as a function of the interstellar P grain fraction, for a 10% and 100% fraction of interstellar S in grains. The derived GCR source  $^{31}\text{P}/^{32}\text{S}$  ratio is plotted as a horizontal line, with dotted lines showing the uncertainty on this ratio.

bearing ices [23]. The sulfur grain fraction in the Horsehead Photodissociation Region was recently calculated to be less than 75%, and can be close to zero if the material is warmer than 30 K.

The interstellar  $^{34}\text{S}/^{32}\text{S}$  was assumed to be about 30% lower than the terrestrial ratio [15] to reflect observations of monosulfides in nearby star-forming regions [24]. The isotopic composition of the ejecta is calculated from the supernovae ejecta and Wolf-Rayet wind yields, and is found to have a larger  $^{34}\text{S}/^{32}\text{S}$  ratio than the interstellar material.

As seen in Figure 2, if 100% of the interstellar sulfur is assumed to be in grains, the superbubble  $^{31}\text{P}/^{32}\text{S}$  ratio is not consistent with the derived ratio in the GCRs for any grain fraction of ISM phosphorus. However, if 10% of the interstellar sulfur is in grains, the superbubble  $^{31}\text{P}/^{32}\text{S}$  ratio is consistent with the observed GCR source ratio at the ISM phosphorus grain fraction observed in the hot ISM [25]. The interstellar material mixed into the superbubble core is hot, much warmer than 30 K, so the 10% interstellar sulfur grain fraction is consistent with that derived in warmer environments [26] and is inconsistent with a large sulfur depletion onto dust grains in the GCR source environment.

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