Confidence Levels for Distinguishing Galactic Cosmic-Ray Source Models

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Abstract

Despite much progress, the origin of galactic cosmic-ray nuclei remains unknown. One of the more promising models for the source of these nuclei is supernova ejecta in superbubbles. In this model, supernova ejecta would be accelerated by other nearby supernovae. There is observational evidence that superbubbles have enhanced metallicity. In particular, we expect that superbubble interiors would have an enhanced abundance of actinides relative to the average interstellar medium. We discuss the expected abundance of cosmic-ray actinides in light of models of actinide yields, superbubble interiors, and interstellar medium chemical evolution. Based on these expected abundances, we calculate the expected statistics for a particular detector, the Extremely heavy Cosmic-Ray Composition Observer (ECCO), and expected confidence limits for distinguishing superbubble models from other possibilities.

1. Introduction

It has been known for some time that supernova shocks can provide the energy source for the galactic cosmic rays (see *e.g.* [4]). However, the source material out of which cosmic rays are accelerated remains obscure. It has been established that a large fraction of supernovae occur in superbubbles [2,8]. Thus, supernova shocks would be expected to accelerate relatively freshly synthesized material left behind by other supernovae. This material should have a characteristic nucleosynthetic age of ∼10–50 Myr. Furthermore, the metallicity of superbubbles is approximately two to three times Solar, as observed in superbubbles in the Large Magellanic Cloud [3] and in a recently-discovered nearby superbubble [7]. If superbubble material is indeed the source of cosmic-ray nuclei, the abundances of the long-lived radioactive actinides (*e.g.* ^{232}Th, ^{238}U, ^{244}Pu, ^{247}Cm) should be significantly different from both Solar and average interstellar medium values.

Based on these ideas, Lingenfelter *et al.* [10] (hereinafter LHKP) have calculated the expected abundances of actinides in the interstellar medium and in galactic cosmic rays. Their work is based on the r-process yield calculations developed using the ETFSI-Q nuclear mass model [9,12]. They have accounted

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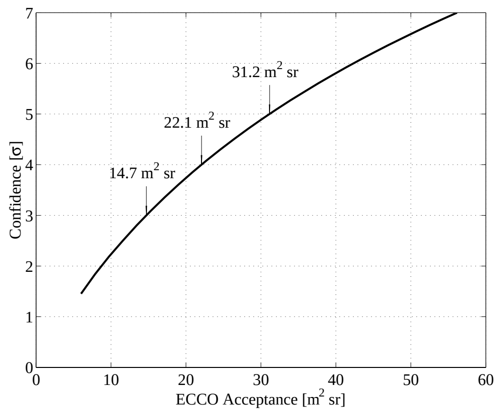

Fig. 1. Sensitivity of ECCO to a superbubble component as a function of acceptance for the LHKP model and a 3 yr exposure. Required acceptances for 3, 4, and 5 σ are shown.

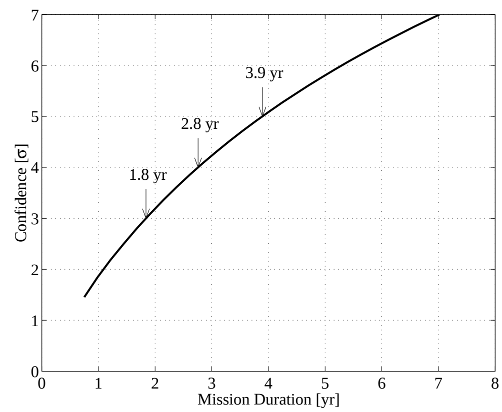

Fig. 2. Similar to Fig. 1., sensitivity as a function of mission duration for a 24 m^2 sr ECCO acceptance.

for superbubble evolution and included contributions from the small fraction of supernovae expected not to explode inside superbubbles. In addition they account for chemical evolution of the interstellar medium since the formation of the Solar System.

The objective of the Extremely Heavy Cosmic-Ray Composition Observer (ECCO) [13] is to distinguish between superbubbles and the average interstellar medium as the origin of galactic cosmic rays. ECCO is designed specifically to measure the abundances of actinides. In order to determine the sensitivity of the ECCO detector to freshly-synthesized material in the cosmic rays, we need both the acceptance of the detector and the flux of the actinides.

2. Acceptance and Sensitivity of ECCO

ECCO has been proposed in a variety of configurations, both as a component of a free-flying satellite and as a payload attached to the International Space Station (ISS). In neither case does ECCO have a simple configuration which would allow a geometrical calculation of acceptance. However, ECCO is a completely modular detector, so we can simulate the acceptance of individual modules and then sum over modules to find the total acceptance.

In order for a particle to be accepted, it must deposit a sufficiently strong signal in the outer hodoscope sheets. This track signal is charge and energy dependent. Actinides are sufficiently highly charged that they produce acceptable tracks at least up to the maximum zenith angle described below. However, lower charges, such as Pb and Pt-group cosmic rays, produce a weaker signal and may not form a sufficient signal at large zenith angles. Thus the solid angle in which

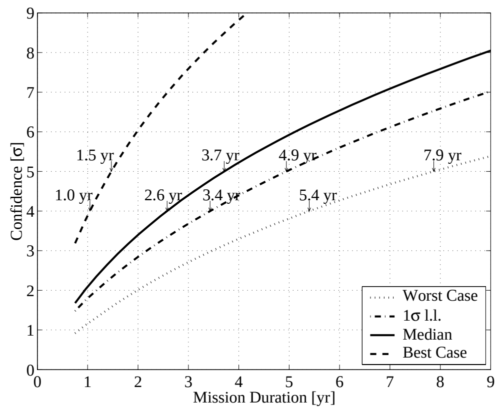

Fig. 3. Similar to Fig. 2., sensitivity of ECCO to a superbubble component as a function of mission duration for selected GA models.

ECCO can accept particles is charge dependent.

In our simulation of ECCO acceptance we have accounted for a large number of effects which reduce the final acceptance. First, we do not accept particles with eneriges below 900 A MeV or with zenith angles greater than 70°. Other effects that reduce acceptance include particle fragmentation in the detector itself and in any overlying structural material, particles which leave the detector before a sufficiently long track can be registered, zenith angle effects already described, and shielding by the limb of the Earth. For ECCO on the ISS, we are also able to include the effects of shielding by other attached payloads. However, due to the complicated geometry of the ISS, we have not at present included shielding by the ISS itself.

In Fig. 1. we have used the LHKP abundances to determine the statistical significance in distinguishing a general interstellar medium source from a superbubble source with metallicity $Z = 2Z_{\odot}$ as a function of ECCO acceptance, based on the measurement of the ratio (U + Pu + Cm)/Th. Abundances were converted to statistics using the cosmic-ray fluxes provided to us by Richard Mewaldt [11]. The confidence level was calculated using the approximate formula of Gehrels [5] for binomial statistics. The flux has been corrected for Solar modulation based on a 2008 launch date. In addition, the actinide abundances have been corrected for the difference in fragmentation cross section relative to the Pt-group in propagation from the source to Earth. We also show in Fig. 2. the significance as a function of mission duration for an acceptance of 24 m^2 sr. This is a value typical of ECCO as an attached payload on the ISS with shielding by a nearby attached payload.

3. Uncertainties in Sensitivity

In order to estimate the theoretical uncertainties in actinide abundances due to different r-process yield calculations, we have examined the 32 models of actinide abundances as calculated by Goriely and Arnould [6] (hereinafter GA).

Actinide yields are typically expressed in units scaled to Si $\equiv 10^6$. However, the actinides are very far away in nuclear mass from Si, and in any case, are produced in completely different nucleosynthetic processes. Thus, theoretical calculations of actinide to Si ratios are necessarily somewhat uncertain. Fortunately, it is possible to normalize actinide yields to the protosolar Th and U abundances, which are well known (*e.g.* [1]). We assume that the same r-process produced both Solar and cosmic-ray actinides. In order to simplify the calculation, we assume all Solar actinides were produced by a single r-process event. While this is physically unrealistic, a distribution of r-process events over time results in more actinides than a single event, so this is a conservative assumption. We determine the time delay between the r-process event and the formation of the Solar System required to produce the observed U/Th ratio. Then we use this time delay to compute the correction to the absolute Th yield required to produce the protosolar Th abundance. All actinide abundances in this model are then renormalized using this correction factor. With these absolute yields we can again calculate confidence levels as with the LHKP model. The results of this study for selected GA models are shown in Fig. 3.

4. Conclusion

We have computed the acceptance and sensitivity of ECCO to actinides in a variety of r-process scenarios. These results make clear that ECCO can distinguish between a superbubble source and a source more characteristic of the average interstellar medium with high confidence level.

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