Actinides and the Sources of Cosmic Rays

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Abstract

The abundances of the actinide elements in the cosmic rays can provide critical constraints on the major sites of their acceleration. Using recent calculations of the r-process yields in core-collapse supernovae (SNe), we have determined the actinide abundances averaged over various assumed time intervals for their supernova generation and their cosmic-ray acceleration. Using standard Galactic chemical evolution models, we have also determined the expected actinide abundances in the present interstellar medium. From these two components, we have calculated the U/Th and other actinide abundances expected in the SN-active cores of superbubbles, as a function of their ages and mean metallicity. We calculate the expected actinide abundances in cosmic-rays accelerated by Galactic SNe. We find that the current measurements of actinide/Pt-group and preliminary estimates of the UPuCM/Th ratio in cosmic rays are all consistent with the expected values if superbubble cores have mean metallicities of around 3 times solar. Future measurements of the abundance ratios will help to solve these questions. First results of experiments performed on the MIR space station (ECCO) and with balloon flights (TIGER) are promising.

Key words: Cosmic rays, Galaxy: evolution, nuclear reactions, nucleosynthesis, abundances, supernovae: general
PACS: 95.85.Ry, 98.35.Ac, 96.40.DE, 26.30.+k, 97.60.BW

Supernova shocks are generally thought to provide the energy for the acceleration of Galactic cosmic rays (ranging up to the actinides), but the source material as well as the acceleration mechanism are open questions. The similarity in the abundance ratios between ultra-heavy cosmic rays (UHCR) and the interstellar medium (ISM) suggested that they may be accelerated out of the well-mixed ISM. But, since most of the heavy elements are ejected into the ISM by SN (which are clustered in space and time), the relative abundance ratios will not differ between these fresh ejecta and the well-mixed ISM (see

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Preprint submitted to Elsevier Science *18 September 2003*

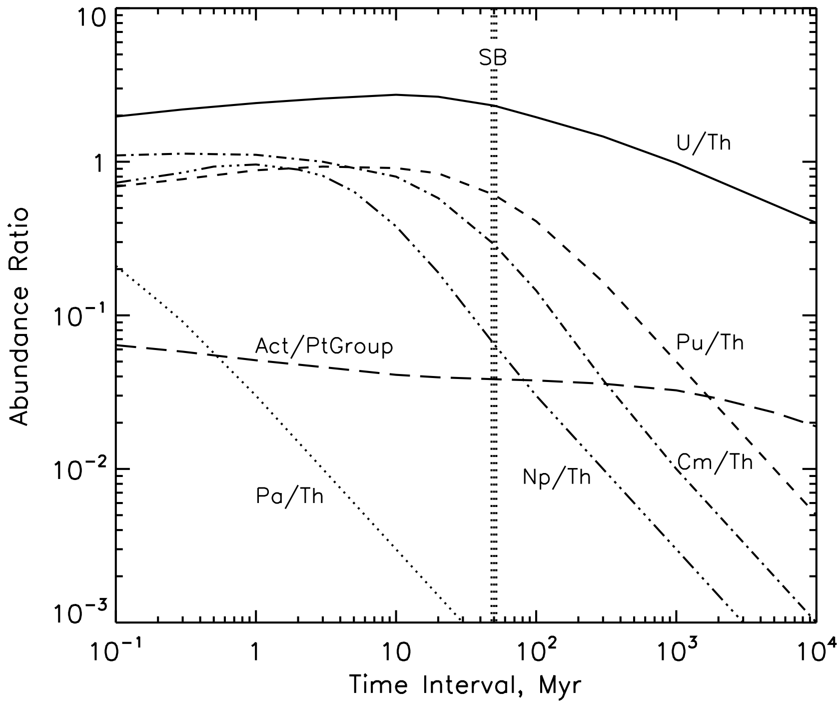

Fig. 1. Mean actinide abundance ratios from r-process yields in core-collapse SNe in their accumulating ejecta averaged over various time intervals, assuming a constant SN rate during those intervals. The typical cosmic ray acceleration time span in the SN-active cores of superbubbles of roughly 50 Myr is indicated by the dashed vertical line (SB).

ref. [1] and references therein). However, because they are radioactive, the UHCR abundances of the actinide elements, Th, U, Pu and Cm, can provide critical constraints on the major sites of their acceleration and metallicity, as well as on the time scales involved [2]. The longest lived isotopes of these elements have decay mean lives of 20.3 Gyr for ^{232}Th, 6.45 Gyr for ^{238}U, 115 Myr for ^{244}Pu, 22.5 Myr for ^{247}Cm, and 3.09 Myr for ^{237}Np [3]. Starting about 50 Myr ago, the shock waves of SNe from a giant OB association blew an enormous bubble in the ISM, the ~ 1 kpc large local superbubble of rarefied ISM, in the core of which the SN ejecta was mixed and from which most local cosmic rays were accelerated. The outer expanding shell is marked by new star-forming regions of young, hot OB associations in Gould's Belt. Because of their short destruction path lengths, the most probable source for the UHCR are the about 20 SNe explosions which took place over the last 10 MYr in the close-lying Scorpius-Centaurus OB associations [4]. The recently detected live radio-isotopes in terrestrial archives (as ^{60}Fe in deep-sea sediments [5]) are signatures of these recent, nearby SNe [6]. The isotopic r-process yields of stable elements are obtained from primitive meteorites. In order to calculate the expected range of actinide abundances in the cosmic rays, we use recent calculations of r-process yields in core-collapse SNe in the framework

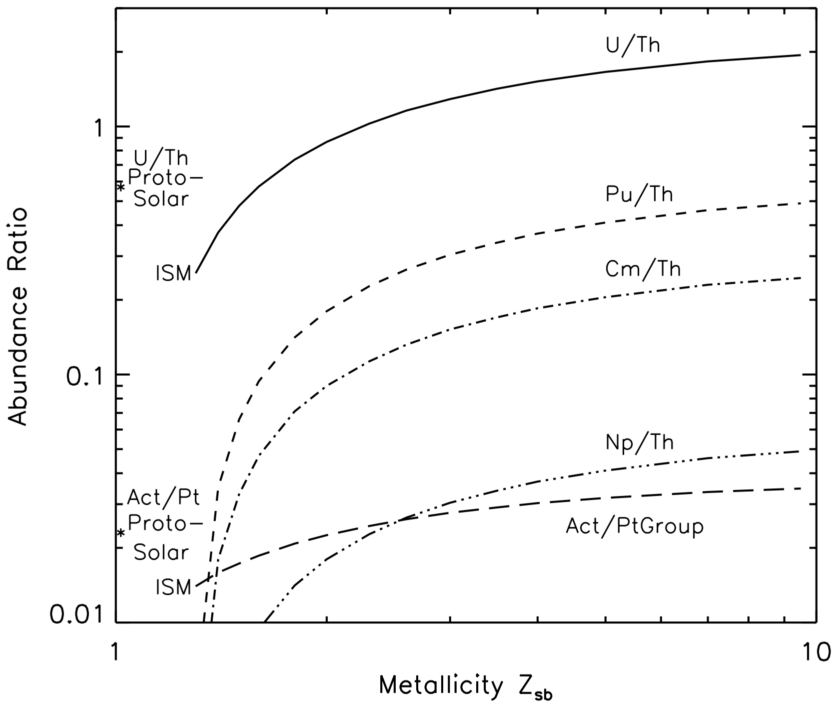

Fig. 2. Expected cosmic-ray actinide abundance ratios as a function of superbubble core metallicity. Also indicated are the estimated U/Th and Actinide/Pt-Group (Z = 75 to 79) ratios in the current interstellar medium (ISM) and in the SN-enriched proto-solar material.

of a canonical r-process within the "waiting-point approximation" [7,8]. As the r-process involves extremely neutron-rich isotopes, the majority of the nuclear-physics input data have to be derived from nuclear theories. In order to check their validity far from stability, we have compared the prediction to the steadily increasing experimental data base over the last decade [9].

The r-process calculations, which use the ETFSI-Q atomic mass model [10], have yielded results that are in excellent agreement with the observed solar r-process abundances and also with those observed in metal-poor Halo stars (see, e.g. [11] and Fig. 1 in ref. [12]). From these yields the actinide abundances in the cosmic rays averaged over time following the SN explosions are predicted (see, Fig. 1 and ref. [2]). Using standard Galactic chemical evolution models, the expected actinide abundances in the present day ISM and in the SN-active cores of superbubbles are calculated as a function of their ages and mean metallicity resulting from dilution with interstellar clouds (see, Fig. 2 and ref. [2]). The current measurements of the actinide/Pt-group ratios [13] and preliminary estimates of the UPuCm/Th ratio in cosmic rays [14] are consistent with the predictions if superbubble cores have metallicities of 3 times solar. Recently, Higdon and Lingenfelter demonstrated that the cosmic-ray source abundance ratio of $^{22}Ne/^{20}Ne$ can be understood as the result of cosmic rays accelerated out of superbubble cores with a mean metallicity of about 3 times solar [15].

In future, more precise measurements of the abundance ratios with improved statistics will help to obtain a better measure of the mean source metallicity sampled by the local Galactic cosmic rays. First results of experiments performed on the MIR space station (ECCO [16]) and with ultra-long duration balloon flights (TIGER [17], which serves as an engineering model for the future Heavy Nuclei Explorer mission) are promising. In addition to meteoritic material and optical spectroscopy of stars, with actinide cosmic rays a new window to extra-solar matter is opened.

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