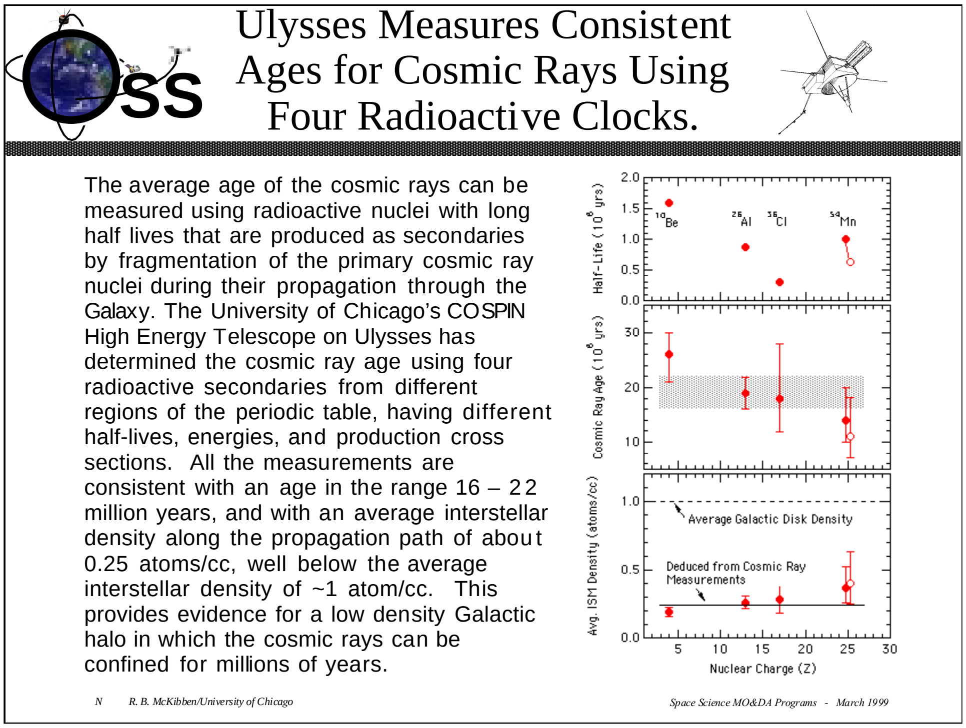

Ulysses Measures Consistent Ages for Cosmic Rays Using Four Radioactive Clocks.

The average age of the cosmic rays can be measured using radioactive nuclei with long half lives that are produced as secondaries by fragmentation of the primary cosmic ray nuclei during their propagation through the Galaxy. The University of Chicago's COSPIN High Energy Telescope on Ulysses has determined the cosmic ray age using four radioactive secondaries from different regions of the periodic table, having different half-lives, energies, and production cross sections. All the measurements are consistent with an age in the range 16 – 22 million years, and with an average interstellar density along the propagation path of about 0.25 atoms/cc, well below the average interstellar density of ~1 atom/cc. This provides evidence for a low density Galactic halo in which the cosmic rays can be confined for millions of years.

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After acceleration, cosmic rays diffuse through the magnetic fields in the galaxy before finally escaping. During propagation, primary cosmic ray nuclei interact with interstellar material to produce secondary nuclei, some of which are radioactive. Secondary radioactive nuclei with half-lives of order 1 million years (1 MY) provide a way to measure the average time that the cosmic rays are confined in the galaxy.

In the 1970s the IMP 7 and 8 satellites made the first measurement of the cosmic ray age using ^{10}Be(1), which has a half-life of ~1.6 MY. Cosmic ray Beryllium is produced almost entirely by spallation of heavier primary cosmic rays during their propagation in the galaxy. Of ~420 Be nuclei detected, ~20 were ^{10}Be. This implied that almost all of the ^{10}Be produced had decayed. While the ^{10}Be/Be ratio gave a measure of the average time spent in propagation, measurement of the ratio of the more abundant secondary, Boron, to the primary Carbon provided a measure of the total amount of material the cosmic rays had passed through. Knowing the velocity of the cosmic rays, the lifetime measurement then also yielded the average density of material along the cosmic ray path. Analysis of these observations using a complete model of interstellar propagation and escape gave an average age of ~20 MY, and an average density of ~0.2 atoms/cc, much less than the overall average of ~1 atom/cc in the galactic disk.

Prior to Ulysses the instruments in space could not separate the radioactive isotopes of other, heavier, secondary elements. With the large geometrical factor and high resolution of the COSPIN HET, the ^{10}Be analysis was repeated with more than 1500 Be nuclei(2). We have also studied ^{26}Al(3), ^{36}Cl(4), and ^{54}Mn(5), which have half-lives ranging from 0.3 to ~1 MY. All the measurements give consistent lifetimes around 20 MY, and densities around 0.25 atoms/cc. The consistency of the cosmic ray age measurements is important because the isotopes we have used are produced from different primaries, with different cross-sections, and at different energies. This consistency provides strong evidence for the existence of a low density galactic halo in which cosmic rays spend much of their time after they are accelerated. Prior to this work, the beta-decay half-life of the fully stripped ^{54}Mn nucleus, as found in cosmic rays, was very poorly known. In the lab this decay is masked by a very much more probable (half-life = 312 days) electron capture decay. Estimates for the beta-decay half-life ranged from 0.1 to 10 MY, and our initial analysis(5) assumed a value of 1 MY. Inspired by our measurements, Wuosmaa et al.(6), with our participation, undertook a laboratory measurement to further refine the ^{54}Mn beta-decay half-life. They obtained a value of 0.63 MY. Open circles in the figure indicate the results of using this newer half-life in our analysis.

(1) Garcia-Munoz, Mason, and Simpson, *Ap. J.*, **217**, 859, 1977. (3) Simpson and Connell, *Ap. J. Lett.*, **497,** L85, 1998. (4) Connell, DuVernois, and Simpson, *Ap. J. Lett.*, **509**, L97, 1998. (5) DuVernois, *Ap. J.*, **481**, 241, 1997 (Ph.D. Thesis) (6) Wuosmaa et al., *Phys. Rev. Let.*, **80**, 2085, 1998.