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Superbubbles and Local Cosmic Rays

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We consider the possibility that distinctive features of the local cosmic ray spectra and composition are influenced by the Solar system being embedded within the cavity of an ancient superbubble. The “knee” and “second knee” may be understood in this picture, which also predicts several shifts in the element composition of the cosmic radiation between 10^{11} and 10^{20} eV,

1. Introduction

Soon after the discovery of supershells in the late 1970s, it was suggested that the Solar system was located in the interior of such a shell, and that some features of the observed cosmic radiation might be explained by this fact [1], [2], [3]. Since that time, evidence from low-energy isotopic composition and K-capture nuclei [4], [5] has lent strength to models [6] of cosmic ray origin in which acceleration takes place in the environment of a superbubble. In the same period, observations of high-energy spectra have been dramatically improved, e.g. [7]. Here, we reconsider the possible consequences of generation and confinement of cosmic radiation within a superbubble.

2. Superbubbles

Superbubbles are large 100-parsec-to-kiloparsec size shells of gas that are believed to be formed by sequential supernovae explosions in OB associations [8]. The interior cavity of the shell is hot and low density, with the majority of interstellar gas having been swept into the shell wall. Ages of superbubbles can range from a few millions years to many tens of millions of years.

When considering the possibility of cosmic rays accelerated and then confined within the cavity of a superbubble, a crucial matter is the configuration of the magnetic field associated with the superbubble. Streitmatter et al. [3] suggested that a 500 pc elliptical shell associated with Gould’s Belt (Feature A, the Lindblad Ring) might be responsible for confinement of local cosmic rays, and argued on dimensional grounds that the magnetic structure of the shell should be of order 50 parsecs thick. Ferriere et al. [9] considered the effects of interstellar magnetic fields on the evolution and structure of a superbubble, considering the simple case of expansion of a superbubble in a uniform magnetic field. Using both analytical and numerical methods they found that magnetic fields of Galactic strength do little to modify the bubble external size and shape. Within the shell, however, magnetic pressure exceeds gas pressure and causes substantial thickening of the shell and consequent reduction of the cavity size. Troland and Heiles [10] use Zeeman effect measurements to estimate the magnetic field in the 300 parsec diameter Eridanus shell to be 15 μgauss.

Korpi et al. [11] carried out sophisticated 3-dimensional MHD simulations of superbubble evolution in a complex, turbulent inhomogeneous ISM with hot, warm and cold gasses, as well as a magnetic field having both uniform and random components. They found that in this case expanding superbubbles quickly lose their spherical symmetry and acquire irregular shapes. The characteristic feature of a hot, low-density cavity from which magnetic fields and gas have been expelled persists, but the geometry of the cavity evolves dynamically, affected by SN both within and exterior to the cavity. Work by previous authors (e.g. [12])

simulating SB expansion in a model with density stratification uniform in planes parallel to the Galactic disk and a uniform magnetic field had indicted that SB could only "blow out" (magnetically rupture) into the Galactic halo at great age if at all. In contrast, Korpi et al., found that SB evolving in an inhomogeneous, turbulent ISM could develop chimney-like structures opening the bubble at its "top". However, these chimneys were typically transient having lifetimes of only a few million years, with the SB reclosing as the ISM was mixed and stirred by fresh SN and possible interaction with adjacent bubbles. The simulations of Korpi et al. also produced complex structures with tunnel-like features connecting low-density volumes, in agreement with the predictions of Cox and Smith [13].

Our own Solar system is within in the Local Bubble (LB), a hot ($T \approx 10^6$ K), low-density ($n \approx 0.005/cm^3$) volume of approximately 150 parsec dimension. Lallement et al. [14] collected line-of-sight spectral absorption data on more than one thousand stars to construct a three dimensional map of dense neutral gas around the Local Bubble. In the Galactic plane, they found the LB to be highly irregular with "walls" of neutral gas surrounding it at distances varying from 65 to 150 parsec from the Solar system. Several "tunnels" lead from the LB to adjacent cavities. The complex irregular shape is attributed to the LB being "squeezed" by surrounding shells. At high latitudes, the smallest absorption was found in two chimneys, above and below the Galactic plane, whose directions are perpendicular to the plane of the Gould Belt, which is tilted some 17 degrees to the Galactic plane. This may indicate that the LB is magnetically open to cosmic ray escape at the "top" and "bottom". Another possibility is that ionized gas previously trapped in the magnetic field has neutralized and fallen away, leaving the field intact. Frisch [15] notes that toward the north Galactic pole, more than half of all HI is infalling toward to Galactic plane, and suggests this may be the evolved shell of the LB collapsing under gravitational force.

3. Local Cosmic Rays, Toy Model

We consider a scenario in which energy spectra of elemental cosmic rays are generated within the local cavity of a SB and confined against escape with an energy-dependent time constant that is large at small energies and small at large energies. Loosely, at low energies the SB is closed, and at high energies it is open. We further assume that exterior to the SB there also exists a spectrum of cosmic rays, not necessarily with the same spectral index, that may leak into the SB with the same energy-dependent time constant. What will be the spectra and composition of cosmic rays within the cavity?

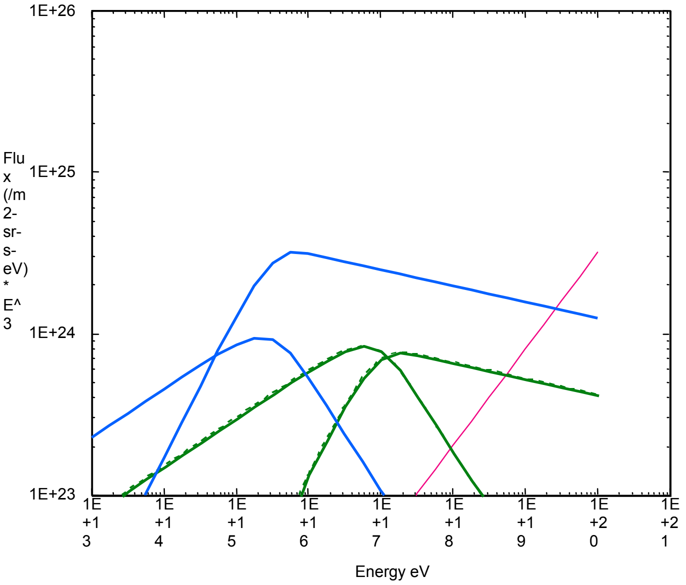

Figure 1. Toy-model spectra within the cavity

To approach this question, we created a toy model with the following features.

(1) Cosmic rays are generated within the cavity interior with an energy spectral index of -2.7. There are only two components, protons and iron, which are normalized at 10 GeV to represent the total cosmic ray flux.

(2) There exists a spectrum of Galactic cosmic rays exterior to the SB that have an energy spectral index of -3.1. There are only two components, protons and iron, which are normalized at 3 x 10^{18} eV to represent the total cosmic ray flux.

(3) Leakage for cosmic rays into or out of the SB has a rigidity-dependant time constant $T_L=C_0 \exp(-R/R_k)$. For specificity, R_k is chosen as 4 x 10^{15} GV, i.e. the rigidity of protons near the knee. C_0 is chosen as 1.2 x 10^7 years, and a bubble age of 3 x 10^7 years is assumed.

(4) There is an "extragalactic" proton spectrum, which begins to dominate flux above the ankle.

Under the assumptions above, simple calculation leads to Figure 1, which displays the five spectra that contribute to the cosmic rays interior to the SB cavity. As customary, the spectra have been multiplied by E^3 to facilitate display of features. All the spectra are those observed in the SB. The spectrum labels refer to the place of origin. The "P interior" spectrum maintains a slope of -2.7 until it approaches the energy corresponding to R_k for protons, 4 x 10^{15} eV. Beyond that energy, as the leakage time constant becomes small compared to the bubble age, the protons generated within the bubble escape and the spectrum plunges. Similar remarks apply to the "Fe interior" spectrum (dashed), with leakage surpressing the spectrum above R_k, corresponding to an energy around 10^{17} eV. At high energies, the exterior proton spectrum leaks into the bubble easily. As R_k is approached from above the leakage time constant become large, and the fraction of the exterior proton spectrum reaching the interior falls at lower energies.

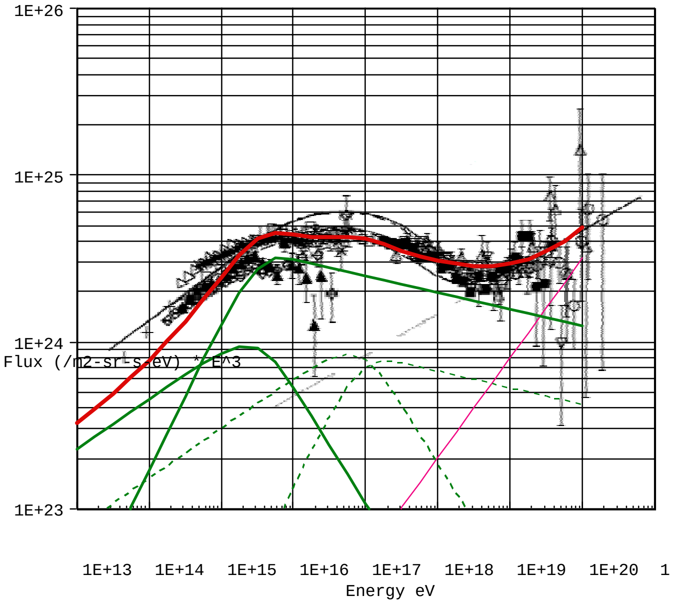

Figure 2: Toy-model with EAS data

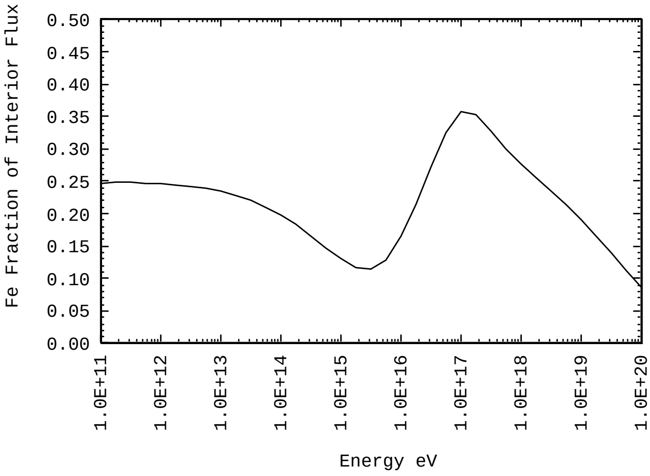

Figure 3. Toy-model Fe Faction vs Energy

In Figure 2, the toy-model is compared with a summary of EAS data adapted from Roulet [16]. The bold line is the total cosmic ray flux. Several features are worth noting. (1) The knee results from the transition between interior-produced and exterior-produced proton spectra. The fluxes are not in fact matched at the knee. Rather, the model predicts a brief upturn in the proton spectral slope in the half decade before the knee. (2) The "second knee" is explained in this model as the transition energy between the dominance of the iron spectrum by interior-produced and exterior-produced iron. (3) Examination of the several spectra shows interesting shifts with energy of the p/Fe ratio.

Figure 3 displays the toy-model fraction of flux that is iron as a function of energy. As the knee is approached from below, the exterior-produced proton spectrum reduces the iron fraction. Above the knee, the fraction of iron rises as a result of the falling interior-produced proton spectrum and the combined flux of interior-produced and exterior-produced Fe. The model predicts that the second knee at 10^{17} eV is the energy at which the fraction of Fe peaks.

Discussion

As an explanation of the cosmic ray spectra observed at Earth, the superbubble model departs from conventional wisdom in various ways.

There is no $E^{-0.5}$ dependence of escape lifetime to bridge the difference between theoretical expectation of spectral index ($\approx$ -2.0 to –2.2) and the observed slope of –2.7. Rather, the exponential dependence of the leakage time constant results in a relatively quick transition from slow-leakage to fast-leakage. This results in a “sharp” knee.

The essential feature of the superbubble model is two separate reservoirs of cosmic rays, with a rigidity filter that mediates between them. In the particular case of the Solar system, it is questionable, albeit possible, that the Local Bubble can retain “interior” cosmic rays up to energies around 10^{15} eV. In this regard, one notes that the gyroradius of a 4 x 10^{15} eV proton in a 5 μgauss field is only about 1 parsec. As to the “exterior” flux in the model, it is not implausible that the Galaxy retains a flux of cosmic rays in the energy range from 10^{15} – 10^{18} eV with a spectral index of $\approx$ -3.1. Indeed, that is the conventional view. However, this spectrum can not continue down to the GeV range without violating constraints from gamma-ray fluxes.

The superbubble model has the virtue of solving the long-standing problem of the isotropy of the cosmic radiation (few x 10^{-4}) in the face of predictions by other models of extremely short lifetimes in the Galaxy. The second knee is explained and a somewhat surprising energy variation of the iron (more generically, heavy) fraction is predicted.

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