

## Low-Energy Cosmic Rays

Cosmic rays, broadly defined, are charged particles from outside the solar system. These can be electrons, protons, or ions; the latter two dominate the number observed. They are called cosmic “rays” because initially it was thought that they are a type of photon. Study of low-energy cosmic rays tells us about the composition and density of the interstellar medium and, importantly, about the formation and dispersal of heavy elements in the galaxy. Study of the highest energy cosmic rays, which we will discuss in the next lecture, may reveal new physics and even if it doesn’t, it tells us a lot about acceleration processes and the intergalactic medium.

The observation of cosmic rays has challenges quite different from the observation of photons. **Ask class:** what are some of the differences? A major one is that, being charged particles, cosmic rays are deflected by magnetic fields. These fields can be in the intergalactic or interstellar medium, or in the solar system itself. This deflection limits the available angular resolution for high energy cosmic rays, and renders any angular resolution impossible below a certain energy, since the average deflection angle exceeds  $180^\circ$ . Another difference is that many nuclei are radioactive. If the half-life is comparable to or less than the propagation time in the rest frame of the nucleus, such radioactive nuclei will decay. This means that by measuring isotopic composition one has a clock indicating how long the cosmic rays have been propagating. A third difference is that because nuclei are complex particles (unlike photons), a collision can split the nucleus (this is called “spallation”). By knowing the spallation cross section at a given energy, one therefore has an indication of the total column depth of material traversed. A fourth difference has to do with the information available: for a photon, the information is its energy, direction, and polarization. For a cosmic ray, the information is the energy and the type of particle, although type of particle is tough to measure at high energies.

### The energy spectra of cosmic rays

The general spectrum of cosmic rays, from 1 GeV per nucleon on up, is an amazingly good power law. The number flux between energies  $E$  and  $E + dE$  is  $N(E)dE = KE^{-x}dE$ , with  $x = 2.5 - 2.7$  over most of the range. Around a total energy of  $10^{15}$  eV, the spectrum becomes slightly steeper (higher  $x$ ), and around  $10^{18-19}$  eV it becomes slightly shallower again. These are therefore referred to as the “knee” and the “ankle” of the cosmic ray distribution.

Below about 1 GeV per nucleon, the number flux drops dramatically below the extended power law. **Ask class:** assuming that there is no true drop in the population, what effect might explain this? At a low enough energy, the solar wind and its associated magnetic field is able to prevent the propagation of charged particles. This is therefore an artifact. Of

course, there also has to be a real cutoff at some point (a power law extended indefinitely would mean an infinite number of particles!), but this means that, as always in astronomy, one has to be cautious about inferences based on raw data. There is always an interpretation involved.

This leads us again into the issue of propagation through a region with magnetic fields. **Ask class:** given two otherwise identical particles, which is affected more, one with more momentum or one with less? The one with less momentum. **Ask class:** given two otherwise identical particles, which is affected more, one with more charge or one with less? The one with more charge. In both cases, it's a question of the gyroradius of the particle in the magnetic field. In fact, it turns out that there is a quantity called the rigidity,  $R = pc/ze$  (where  $p$  is the relativistic three-momentum and  $ze$  is the charge), which uniquely determines the dynamics of a charged particle in a magnetic field. For two particles with the same velocity and hence the same Lorentz factor,  $R = (A/z)(m_p\gamma v c/e)$ , so the rigidity depends only on  $A/z$ . **Ask class:** what is the approximate value of  $A/z$ , for elements less massive than iron? About 2, so different particles with the same energy per nucleon behave similarly.

### **The elemental abundance of cosmic rays**

This is where contact is made with the synthesis of elements in stars, particularly heavy elements and those formed in r-process neutron capture in supernovae. The net result is that elemental abundances are not very different from those of typical abundances in the Solar System. The major difference is that light elements (lithium, beryllium, and boron) are dramatically overabundant in cosmic rays compared to the Solar System, and that cosmic rays of elements somewhat lighter than iron are somewhat overabundant. Both of these excesses are thought to be due to spallation. Another way to get at the properties of cosmic rays is to look at different isotopes of the same element. The cross section for spallation is not going to be very different between different isotopes, so this gives a better idea of the original composition before any spallation. In addition, as mentioned earlier, many isotopes (especially those produced only by spallation) are radioactive, so they act as clocks. A particularly good clock is  $^{10}\text{Be}$ , which has a half-life of  $3.9 \times 10^6$  yr, which is comparable to typical diffusion times through the disk of the Galaxy. There tends to be an overabundance of neutron rich isotopes in cosmic rays compared to their abundance in the Solar System, but the overabundance factor isn't huge: e.g.,  $^{25}\text{Mg}/^{24}\text{Mg}$  is about 1.6 times greater than in the Solar System.

### **The isotropy and energy density of cosmic rays**

The local magnetic field in the interplanetary medium is about  $10^{-4}$  G. This means that protons with  $\gamma = 10^3$ , i.e., energies of about 1 TeV, have gyroradii that are

$r_g = 3 \times 10^{11} \gamma (B/10^{-4} \text{ G}) = 3 \times 10^{14} \text{ cm}$ , or about 20 AU. Therefore, protons with energies this great or greater can maintain their directions once in the Solar region.

In addition, highly relativistic particles interact with the Earth's atmosphere to produce an air shower, as discussed earlier in the course. The shower is composed of relativistic particles that themselves preserve the original direction fairly well, so ground-based observations can determine the direction of the cosmic ray with reasonable accuracy, as well as its original energy. Observations of cosmic rays show that the arrival directions are relatively isotropic, and in fact the lower the energy (down to  $10^{12} \text{ eV}$ ) the more isotropic the distribution of cosmic ray directions. **Ask class:** why would the directions be more isotropic at lower energies? Because the gyroradii are smaller, so the particles are deflected more from their original direction. If a nucleus spends significant time outside the disk of our galaxy, it will go a longer distance (hence the abundance of some radioactive elements will be less) but will encounter a small column depth of matter, because the density is less. It will therefore spall less, as could be seen by abundances of lighter spallation products. In this way, people can deduce the fraction of time spent in and out of the disk.

The total energy density of cosmic rays with energies greater than 1 GeV is about  $1 \text{ eV cm}^{-3}$ . This is comparable to the energy density in the interstellar magnetic field,  $0.2 \text{ eV cm}^{-3}$ , to the local energy density in starlight,  $0.3 \text{ eV cm}^{-3}$ , and to the energy density in the cosmic microwave background,  $0.3 \text{ eV cm}^{-3}$ . Some of this must be coincidental (the starlight energy density in globular clusters is thousands of times what it is locally), but some may have meaning (for example, the energy density in charged cosmic rays may have something to do with the magnetic fields, through their interaction).

Suppose that cosmic rays streamed without being bent by the magnetic field, and that they all travel near the speed of light. **Ask class:** how would we go from the observed energy density to the luminosity (energy per time) required for cosmic rays? We would multiply the energy density by the velocity to get the flux, then multiply the flux by the area of the galaxy to get the luminosity. This calculation yields about  $10^{44} \text{ erg s}^{-1}$ , whereas it is thought that the true energy production rate is more like  $10^{41-42} \text{ erg s}^{-1}$ . **Ask class:** what could have gone wrong? Since the particles are deflected by the field, the effective velocity outward is much less than the instantaneous speed, so the true inference should be of a lower energy flux. As a caveat, since the diffusion time of charged particles is long (millions of years, typically), a single unusual event (such as a gamma-ray burst) that happened nearby in the last million years could give a misleading impression of the total energetics. Observations of other galaxies, however, suggest that this is not the case. The total power in cosmic rays is comparable to the kinetic energy in supernovae, so most people think that supernovae are the source of at least the cosmic rays with energies less than about  $10^{15} \text{ eV}$ . Score another for Fritz Zwicky (and Walter Baade), who suggested the SN-CR connection in 1934.

## Cosmic ray propagation and the leaky box model

Detailed calculations show that high energy particles typically traverse about  $\Sigma=5 \text{ g cm}^{-2}$  of matter. If they went through more, then all the primary species of nuclei would be destroyed; if they went through less, then no secondary species would be produced by spallation. **Ask class:** from this, how do we figure out the typical path length of a particle in the interstellar medium? The average density of the ISM is around  $1 \text{ cm}^{-3}$ , or about  $\rho = 1.7 \times 10^{-24} \text{ g cm}^{-3}$ , so the total path length is  $\Sigma/\rho \approx 3 \times 10^{24} \text{ cm}$ . For particles traveling at the speed of light, that's  $10^{14} \text{ s}$ , or about  $3 \times 10^6 \text{ yr}$ . If the particles spent a lot of time in lower-density regions, they could propagate for much longer. **Ask class:** how can we distinguish between the two cases;  $3 \times 10^6 \text{ yr}$  spent in typical ISM densities, versus a lot longer spent in a lower average density? The abundance of radioactive elements with lifetimes of a few million years helps break the degeneracy.

In any case, since the typical dimensions of the Galaxy are only 1-10 kpc, free-streaming cosmic rays would only take  $3 \times 10^{3-4} \text{ yr}$  to escape. Therefore, cosmic rays are confined in some sense. An often-used model is the “leaky box” model of confinement. In this model, cosmic rays move freely inside some volume of confinement, and every time they hit the boundary they have some probability of escape. This results in an exponential path length or propagation time distribution:  $N \propto \exp(-t/\tau_e)$ , where  $\tau_e$  is the characteristic escape time. This confinement volume could be the size of the disk of our Galaxy (thickness 300-500 pc, radius 10-15 kpc), or it could be the halo. Such a halo of high-energy particles is thought to exist because there is a magnetic instability with hot plasma that will cause a “kink” in the field to extend and rise, forming a bubble of the hot plasma.

Then, as mentioned above, we can distinguish between time in the halo and time in the disk by looking at the abundances of radioactive isotopes relative to stable isotopes of the same element. One particularly useful isotope is  $^{10}\text{Be}$ , which is produced by spallation of carbon and oxygen; about 10% of the beryllium produced this way is  $^{10}\text{Be}$ , the rest being stable. The rest-frame decay time is  $3.9 \times 10^6 \text{ yr}$ , into  $^{10}\text{B}$ . Comparison of the relative abundances of  $^{10}\text{B}$  and  $^{10}\text{Be}$  as a function of energy gives information about the total time of propagation, which combined with the  $5 \text{ g cm}^{-2}$  traversed indicates the average density of the material in the path of the cosmic rays. The net result is that the average density is about  $0.2 \text{ g cm}^{-3}$ , and the escape times are  $\tau_e \approx 10^7 \text{ yr}$ . Therefore, most of the time the particles spend is in regions of average density much less than the average density of gas in the Galactic disk.

## The origin of cosmic rays

We close with a few thoughts on what makes cosmic rays. We will leave the question of the origin of the highest-energy cosmic rays for next class, and concentrate on those below

the ankle (below about  $10^{19}$  eV). The salient issues are (1) composition, (2) energy spectra, (3) cosmic ray clocks, (4) isotropy, (5) total energetics and acceleration mechanisms. The net result is that a Galactic origin is consistent with the properties of cosmic rays with energies less than about  $10^{19}$  eV, but there are many questions and an extragalactic origin is not ruled out. In the following we compare Galactic and extragalactic models.

*Composition.*—Spallation arguments say that about  $5 \text{ g cm}^{-2}$  are traversed by cosmic rays. This can be accounted for in the Galaxy. However, an extragalactic origin isn't ruled out, because the average density of gas in the universe is so small ( $4 \times 10^{-31} \text{ g cm}^{-3}$ !) that a particle would have to travel 300 Gpc to get such a column depth! So either Galactic or extragalactic propagation is consistent with this.

*Energy spectra.*—The energy spectra of cosmic rays is  $N(E) \propto E^{-2.5}$  or so. But we found earlier in the class that first-order Fermi acceleration typically produces a power-law spectrum like this in many circumstances. So this isn't an argument one way or the other.

*Cosmic ray clocks.*—Looking at radioactive isotopes, the local flux of cosmic rays must have originated  $< 10^7$  yr ago. That's tough to reconcile with a distant extragalactic origin. Some part could have originated farther away, though: e.g., if 25% of cosmic rays originated locally in the last  $10^6$  yr and the rest were from much farther away, the  $^{10}\text{Be}$  content would agree with observation. But other isotopes might not, and this seems an unnecessarily complicated model.

*Isotropy.*—Strong isotropy (at the  $< 0.1\%$  level for TeV cosmic rays) is easy for an extragalactic origin. Can it be explained with a Galactic origin? Yes, and in fact the isotropy diminishes as the energy increases, as would be expected if deflection by the magnetic field of the Galaxy were responsible for the isotropization of the directions.

*Total energetics and acceleration mechanisms.*—As indicated above, local supernovae can account for the total power requirements of all cosmic rays (so can extragalactic sources, easily). The difficulty comes in whether first-order Fermi acceleration can accelerate particles in supernova shocks to more than  $10^{15}$  eV. At this time, it appears difficult. Moreover, since the spectrum steepens at  $10^{15}$  eV, if there is another mechanism that comes in, it has to have a peculiar spectrum (with a strong *positive* slope below  $10^{15}$  eV) so that it doesn't dominate at lower energies. Puzzling.

The best guess now is that supernovae probably explain the cosmic rays below  $10^{15}$  eV; this is being confirmed by the observation of high-energy photons from electron synchrotron radiation from supernova remnants. They may produce the cosmic rays up to  $10^{19}$  eV as well, but it's tougher. At higher energies, though, the isotropy combined with the large gyroradii of particles indicates that the source is extragalactic. It's those  $E > 10^{19}$  eV cosmic rays that we'll talk about in the next lecture.