8.1 Composition and energy distribution
Cosmic rays can be broadly defined as the massive particles, photons (γ rays, X-rays, ultra-violet and infrared radiation, ...), neutrinos, and exotics (WIMPS, axions,...) striking the earth. The primary cosmic rays are those entering the upper atmosphere, the cosmic rays of the interstellar medium. Secondary cosmic rays are those produced by the interactions of the primary rays in the atmosphere or in the earth. Also products of cosmic ray interactions in the interstellar medium (e.g., spallation products from cosmic ray - cosmic ray collisions) are also labeled as secondary cosmic rays. Cosmic rays can be of either galactic (including solar) or extragalactic origin.

If we confine ourselves to the particle constituents (protons, nuclei, leptons), their motion in the galaxy has been roughly randomized by the galactic magnetic field. (We will mention some exceptions to this below.) Thus they provide very little information about the direction of the source. The peak of the distribution in energy is in the range of 100 MeV - 1 GeV. The intensity of cosmic rays of energy 1 GeV/ nucleon or greater is about 1/cm²sec sr. An approximate formula is

\[ I_N(E) \sim 1.8 \left( \frac{E}{\text{GeV}} \right)^\alpha \text{nucleons/cm}^2\text{sec sr} \]

where \( E \) is the energy per nucleon (rest and kinetc) and \( \alpha \sim -2.7 \). The energy density corresponding to this is thus about 1 ev/cm³. This can be compared to the energy density of stellar light of 0.3 eV/cm³.

The principal components of the (primary) cosmic rays are shown Figure 1. This abundance distribution is approximately independent of energy, at least over the dominant energy range of 10 MeV/nucleon through several GeV/nucleon. By mass about 79% of nucleons in cosmic rays are free protons, and about 80% of the remaining nucleons are bound in helium. The composition has been measured by instruments mounted on balloons, satellites, and spacecraft. Figure 2 shows the chemical distribution of the elements in our solar system differs from that of the cosmic rays in some remarkable ways. The most dramatic difference is an enormous enrichment in the cosmic ray abundances for the elements Li/Be/B. Note also that there is enrichment is even Z elements relative to odd Z, when normalized to solar system abundances. Finally the cosmic rays are enriched in the heaviest elements relative to H and He.

As can be seen from Figure 2, many elements heavier than the iron group have been measured with typical abundances of 10⁻⁵ relative to iron. Much of this information was gained from satellite and spacecraft measurements over the last decade. Some of the conclusions: 1) Abundances of even Z elements with 30 \( \lesssim Z \lesssim 60 \) are in reasonable agreement with solar system abundances.
Figure 20.1: Major components of the primary cosmic radiation (from Ref. 1).

Most measurements are made at ground level or near the top of the atmosphere, but there are also measurements of muons and electrons from airplanes and balloons. Fig. 20.3 includes recent measurements of negative muons [3,13,14,15]. Since $\mu^+ (\mu^-)$ are produced in association with $\nu_\mu (\nu_\mu)$, the measurement of muons near the maximum of the intensity curve for the parent pions serves to calibrate the atmospheric $\nu_\mu$ beam [16].

Figure 1: Major components of the primary cosmic rays (from Simpson).
Figure 2: The abundances of cosmic rays are compared with solar abundances.
Table 1: Relative abundances of cosmic ray nuclei at 10.6 GeV/nucleon normalized to oxygen (=1). The oxygen flux at kinetic energy 10.6 GeV/nucleon is $3.26 \times 10^{-6}$/cm$^2$ sec sr (GeV/nucleon)$^{-1}$. From Boezio et al. and Engelmann et al., as quoted by Gaisser and Stanev.

2) In the region $62 \lesssim Z \lesssim 80$, which includes the platinum-lead region, abundances are enhanced relative to solar by about a factor of two. This suggests an enhancement in r-process elements, which dominate this mass region. This is consistent with r-process scenarios we have discussed (e.g., if the r-process site is core-collapse supernovae, then one would expect enrichment in r-process nuclei as supernovae are also believed to be the primary acceleration mechanism for lower energy cosmic rays).

Galactic cosmic rays are fully ionized: the acceleration mechanisms fully strip the ions. Cosmic rays also have an antiparticle component, as measured in the Space Shuttle Discovery AMS (Alpha Magnetic Spectrometer) experiment. The AMS detected about 200 antiprotons above 1 GeV, generally attributed to nuclear collisions of CR particles with interstellar matter.

The energy distribution of cosmic rays from about $10^{10}$eV to about $10^{15}$eV is smooth, with a power-law distribution

$$\text{particles/cm}^2 \text{ sec MeV/n} \propto E^s$$

with $s$ between -1.6 and -1.7. However there is a break or “knee” in the curve at about $10^{15}$ eV. The slope sharpens above this knee (see Figure 3), falling with $s$ ranging from -2.0 to -2.2, eventually steeping to an exponent of above -2.7. The knee is generally is attributed to the fact that supernova acceleration of cosmic rays is limited to about this energy. This would argue that the cosmic rays above this energy either have a different origin, or were further accelerated after production. While this break is commonly attributed to the inability of supernova shocks to accelerate particles to energies beyond the knee, the sharpness of
the knee has troubled many of the experts: it is difficult to find natural models that produce such a defined break.

There is an additional, somewhat less distinct feature at an energy of about $10^{19}$ eV, termed the ankle. Characteristics of this high-energy feature will be discussed later.

8.2 Propagation and origin
The most commonly used toy model for galactic cosmic rays is called the "leaky box" model. It assumes that the cosmic rays are confined within the galactic disk, where the mass density is high, but with some gradual leaking out of the disk. The confining force is the galactic magnetic field, which is on the order of $10^{-7}$ Gauss. A relativistic particle moving in a magnetic field executes a helical path. Using the relation between the momentum $p$, field $B$, and magnetic radius $R$,

$$p_{\perp}(MeV/c) = 3 \times 10^{-4}BR(\text{gauss cm})$$

one sees that a $10^{14}$ eV proton would have a radius of $3 \times 10^{18}$ cm, or 1pc, which is much less than the distance to the Crab nebulae, a potential accelerator for cosmic rays relatively
near earth. Thus cosmic rays from the knee and below will have no memory of their origin when they reach earth. A $10^{18}$ eV proton corresponds to 10 kpc, about the galactic radius. Clearly any cosmic ray much above this energy could be presumed to be extragalactic, unless it can be associated with a local source, which would be possible as the direction of such cosmic rays would point back to their origin. For example, a cosmic ray of energy $10^{20}$ eV would be minimally perturbed by the galactic magnetic field and thus would "point back" to the extragalactic source from which the cosmic ray originated.

The leaky box models cosmic ray production in the galaxy, cosmic ray trapping by magnetic fields and eventual escape, and cosmic ray interactions in the intragalactic medium. This model does a good job in explaining the energy-dependence of the life of cosmic rays (more on this later). But others have argued for other models, including closed models where cosmic rays are fully confined, then explaining isotope lifetimes (see below) through devices such as a combination of a few nearby and many distant cosmic ray sources.

The conventional explanation for the most dramatic isotopic anomaly in the cosmic rays, the enrichment in Li/Be/B by about six orders of magnitude, is that these isotopes are produced in the interstellar medium when accelerated protons collide with C, N, and O. We mentioned this process earlier. The enrichment of odd-A nuclei (these also tend to be relatively rare in their solar distribution since stellar processes tend to favor production of more stable even A nuclei) is also often attributed to spallation reactions off more abundant even-A nuclei. These associations immediately lead to some interesting physics conclusions because, from the known density of cosmic rays (at least in the earth’s vicinity) and from known spallation cross sections, one can estimate the amount of material through which a typical cosmic ray propagates. Although the estimates are model dependent - and probably not sufficiently interesting to go through in detail - the resulting values for the effective thickness are typically 4 - 6 g/cm$^2$. Now the mass density within intragalactic space is about 1 proton/cm$^3$, or about $1.7 \cdot 10^{-24}$ g/cm$^3$. Thus taking a velocity of $c$, we can crudely estimate the cosmic ray lifetime

$$1.7 \times 10^{-24} \text{g/cm}^3 \times (3 \cdot 10^{10} \text{cm/sec}) \times t = (4 - 6) \text{g/cm}^2$$

So this gives

$$t \sim 3 \cdot 10^6 \text{y}$$

This calculation assumes an average galactic mass density that is not known by direct measurement. Thus it is nice that a more direct estimate of the galactic cosmic ray lifetime is provided by cosmic ray radioactive isotopes. The right chronometer is one that has a lifetime in the ballpark of the estimate above. $^{10}$Be, with a lifetime of $1.51 \times 10^6$ y, is thus quite suitable. It is a cosmic ray spallation product: this guarantees that it is born as a cosmic ray. Its abundance can be normalized to those of the other, stable Li/Be/B isotopes: the spallation cross sections are known. Thus the absence of $^{10}$Be in the cosmic ray spectrum would indicate that the typical cosmic ray lifetime is much larger than $1.51 \cdot 10^6$ y. The survival probability should also depend on the $^{10}$Be energy, due to time dilation effects. One
observes a reduction in $^{10}$Be to about (0.2-0.3) of its expected instantaneous production, relative to other Li/Be/B isotopes. From this one concludes

$$t \sim (2 - 3) \cdot 10^7 \text{years}$$

This suggests that the mass density estimate used above (in our first calculation) may have been too high by a factor of 5-10.

In modeling the origin of cosmic rays, the first conclusion, given their richness in metals, is that must come from highly evolved stars such as those that undergo supernovae. We have already noted the abundance of r-process nuclei, which could be taken as a "smoking gun" of supernova dominance, for those who accept that supernovae are the r-process site. However this is clearly not the full picture. Studies of the isotopic composition as the knee is approached shows that the composition changes: the spectrum of protons becomes noticeably steeper in energy, while the iron group elements do not show such a dramatic change. This is qualitatively consistent with the notion that the galactic "accelerator" producing cosmic rays tops out at some maximum confining field strength. Because the acceleration likely scales as $Z_B$, where $Z$ is the charge, the very highest energies should be dominated by the largest $Z$s, the nuclei.

Above the knee - at energies above $10^{16}$ eV the galactic magnetic field is too weak to appreciably trap particles. Thus it is probable that at these high energies the character of the cosmic rays changes from primarily galactic to primarily extragalactic: the trapping that enhances the abundances of lower-energy galactic cosmic rays would not enhance very high energy ones.

The cosmic rays appear to be approximately isotropic – once one gets above about 50 GeV to escape local magnetic effects. An exception is a small anisotropy measured by AGASA, excess events at about $10^{18}$ eV pointing back to the galactic center. An interesting speculation is that these are neutrons, which because of time dilation can reach the solar system once they reach $10^{18}$ eV. If this result is true, it would argue for a central galactic accelerator that (most likely) is capable of accelerating ions up to $10^{18}$ eV per nucleon.

8.3 Energetics and origin of galactic cosmic rays
We now have the basic information needed to calculate the energetics of galactic cosmic rays. If we take the galactic radius as 10 kpc, we have a volume of $10^{68} \text{ cm}^3$. We noted that the energy density of cosmic rays is about 1 eV/cm$^3$. Thus the cosmic ray energy content of the galaxy is about $10^{68}$ eV. We have argued above that the lifetime of cosmic rays might be about $10^7$ years. Thus the energy production in cosmic rays must be about

$$10^{68}\text{eV}/10^7\text{y} \sim 3 \times 10^{54}\text{eV/sec} \sim 5 \times 10^{42}\text{ergs/sec}.$$ 

We mentioned in passing above that there are cosmic ray models that, unlike the leaky box, confine cosmic rays longer – and thus need to contrive localize sources to account for Be,
etc. Thus our energetics calculation could be modified, replacing the leaky box model with one where the cosmic rays were effectively confined over times up to the age of the galaxy. This would extend the dwell times by up to three orders of magnitude, and thus reduce the energetics requirement proportionally. So that in principle would lower the galactic energetic requirement to about $10^{40}$ ergs/sec. The result is a very generous range for the necessary energetics, requiring sources capable of generating between $10^{40}$ and $5 \times 10^{42}$ ergs/sec.

One can quickly show that stellar winds – e.g., the flares our sun produces – are insufficient energetically to produce energy at this rate, even if integrated over the $10^{11}$ potential sources in the galaxy – the integrated energy in stellar flares falls short of the lower bound above by at least one and perhaps two orders of magnitude. But an interesting source is supernovae – they eject large quantities of material, that material includes both protons and nuclei, and the shock wave and associated fields are an acceleration mechanism.

We have seen that the explosion energy of a supernova is about $10^{51}$ ergs, and the estimated rate of Type II supernovae is 1/30 years. Additional contributions would come from rarer classes of core-collapse supernovae, SNIb SNIc. Thus the energy production rate is about $10^{42}$ ergs/sec – close to that estimated above. There are many arguments based on the chemical patterns of cosmic rays that support core-collapse supernovae as a principal mechanism for generating and accelerating cosmic rays. Novae are powered by the accretion onto a white dwarf. The matter is sucked from a large companion star, perhaps a red giant or main sequence star, under conditions that allow periodic thermonuclear runaway reactions on the white dwarf surface. Novae are another plausible contributor. Novae outbursts within our galaxy occur with a frequency of about 100/year with an energy output about $10^{-4}$ that of the ejecta from a core-collapse supernova. Thus the integrated nova output is similar to that of galactic supernovae.

8.4 Solar-system, terrestrial, and atmospheric environmental effects

Cosmic rays measured on earth reflect not only the galactic inventory of cosmic rays, but also the effect of the local environment of our solar system, the earth, and the atmosphere. The sun’s heliosphere – the region of space altered by the solar wind – extends to about 200 AU. The magnetic structure of the heliosphere shields the region against energetic charged particles. This is apparent experimentally from the correlations between induced cosmic ray activity measured on earth and the 11-year solar cycle, as shown in Fig. 4. This correlation is reflected in changes in the chemistry of the atmosphere, such as $^{14}$C production, an important radio-isotope for dating. $^{14}$C is a product of cosmic ray interactions with O in the atmosphere, and the production is anticorrelated with the shielding, and thus with the intensity of solar activity. Interesting, $^{14}$C production also appears to correlate with various long-term climate anomalies of the past 1000 years, such as the Maunder Minimum ($^{14}$C high) and the 12th-Century Maximum (low), leading to some interesting speculations about the solar role in climate change.
Figure 4: The top curve is the cosmic ray flux from the neutron monitor in Climax, Colorado (1953 – 1996). The middle curve is the annual mean variation in the cosmic ray flux as measured by ionization chambers (1937 – 1994). The bottom curve is the relative sunspot number. While there is a clear solar cycle modulation of the cosmic ray flux, the amplitudes are not well correlated. From Svensnak.
There are also more localized effects due to the earth’s magnetic field, a dipolar field that extends from the magnetic poles and thus is roughly parallel to the earth surface at the equator (Fig. 5). If we envision a cosmic ray proton come into the earth at the equation and use 1000 km as a rough trapping radius, then our previous formula

\[ p_\perp (\text{MeV/c}) = 3 \times 10^{-4} BR(\text{gauss cm}) \]

for \( B=0.3 \) Gauss would give a \( p \sim E \sim 10 \) GeV as the energy of the trapped proton. Thus this defines an energy below which charged cosmic rays would not penetrate to the surface, but instead be sharply deflected. This is the reason that so many cosmic ray balloon experiments are done at the poles, where the magnetic fields are weaker away from the earth and more perpendicular to the surface: one can then more easily sample cosmic rays characteristic of the environment away from the immediate terrestrial neighborhood.

The trapping of lower-energy cosmic rays by the earth’s magnetic field in also part of the third effect of the local environment, interactions of the cosmic rays with the atmosphere. The trapping leads to a larger time in the vicinity of upper atmosphere and thus enhances nuclear interactions than can produce all sorts of cosmic ray secondaries. Such secondaries are also produced by higher energy cosmic rays that are not perturbed significantly by the magnetic field, but do interact in the upper atmosphere. The secondaries include pions, muons, new nuclei created by spallation, electrons and positrons, neutrinos, and the high-energy showers produced by very energetic cosmic ray interactions.

The density profile of the atmosphere is approximately exponential with a scale height of about 7.6 km,

\[ \rho(r) = 1.205 \times e^{-r/7600} \text{kg/m}^3. \]

Thus the total amount of matter that a cosmic ray encounters on approaching the earth grows exponentially with decreasing altitude.

8.5 Muons and neutrinos at the earth’s surface and below. The muons and neutrinos, the most penetrating components of the cosmic ray secondaries, result from strong interaction mechanisms that produce pions and kaons through decay chains such as

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

as we have discussed before. Figure 6 illustrates some important features of these and other cosmic ray secondaries. The figure was generated by cascade code calculations that begin with the primary cosmic ray spectrum at the top of the atmosphere, then propagate that spectrum and the associated secondaries through the atmosphere, taking into account the various reactions that produce new particles and degrade their energies. In contrast to the very large flux/energy losses encountered for other secondaries, the muons and neutrinos generally penetrate the atmosphere well. The atmosphere (and earth) are transparent to
neutrinos, while muons typically lose 2 GeV in ionization energy while transiting the atmosphere.

Consequently, muons dominate the charged-particle spectrum at the earth’s surface. They are the most easily measured component of the cosmic rays and also the primary background in a lot of neutrino experiments – the reason such neutrino experiments must go deep underground. The effects of energy loss are illustrated in Figure 7, where the vertical flux of muons at the earth’s surface is compared with the much harder spectrum that results for muons impinging the earth at 75 degrees from vertical. The latter must penetrate much more matter, which then hardens the spectrum.

Muons lose energy by ionization, bremsstrahlung, production of $e^+e^-$ pairs, photonuclear reactions like Compton production, etc. Their range $R$ in standard rock ($Z \sim 11$, $\rho \sim 2.65$ g/cm$^3$) is given in the table. $R$ is given in meters-of-water-equivalent (mwe), or $10^2$ g/cm$^2$. The energy loss is given in terms of $\alpha$,

$$-\frac{dE_\mu}{dx} = \alpha.$$  

The table shows that the energy loss per g/cm$^2$ increases sharply between 100 GeV and 1 TeV, a result of direct bremsstrahlung, pair production, and nuclear reactions taking over from ionization losses, which dominate at lower energy. The former grow linearly with the muon energy. Consistent with the table, a rough rule of thumb is that the net flux of muons underground decreases by an order of magnitude for every 1500 mwe, or about 500m of burial.  

Figure 5: Rough representation of the earth’s magnetic field, which has an average value near the surface of about 0.3 Gauss.
Figure 20.2: Differential spectrum of electrons plus positrons multiplied by $E^3$. The dashed line shows the proton spectrum multiplied by 0.01.

Figure 20.3: Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV estimated from the nucleon flux of Eq. (20.2). The points show measurements of negative muons with $E_{\mu} > 1$ GeV [3,13,14,15]. Because muons typically lose almost two GeV in passing through the atmosphere, the

Figure 6: The solid lines show vertical fluxes of cosmic rays in the atmosphere with energy above 1 GeV, as estimated from parameterized initial nucleon primary fluxes. The points are from measurements of $\mu^-$. From Gaisser and Stanev.
Figure 20.4: Spectrum of muons at $\theta = 0^\circ$ ([18], [20], [21], [22], [23]), and $\theta = 75^\circ$ ([24]).

Figure 20.4 shows the muon energy spectrum at sea level for two angles. At large angles, low energy muons decay before reaching the surface and high energy pions decay before they interact, thus the average muon energy increases. An approximate extrapolation formula valid when muon decay is negligible ($E_\mu > 100 \, \text{GeV}$) and the curvature of the Earth can be neglected ($\theta < 70^\circ$) is

$$dN_\mu/dE_\mu \approx 0.14 E^{-2.7} \mu \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1.7}$$

(20.5)

where the two terms give the contribution of pions and charged kaons. Eq. (20.5) neglects a small contribution from charm and heavier flavors which is negligible except at very high energy [27].

The muon charge ratio reflects the excess of $\pi^+$ over $\pi^-$ in the forward fragmentation region of proton initiated interactions together with the fact that there are more protons than neutrons in the primary spectrum. The charge ratio is between 1.1 and 1.4 from 1 GeV to 100 GeV [18,23]. Below 1 GeV there is a systematic dependence on location due to geomagnetic effects. [23]

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Figure 7: The spectrum of muons at the earth’s surface at $\theta = 0$ degrees (solid points) and 75 degrees (open diamonds). From Gaisser and Stanev.
standard rock.

Some of you may know that there has been great interest in establishing underground laboratories in the U.S. for sensitive dark matter, neutrino, and nucleon decay experiments. While Europe has facilities like Gran Sasso and Frejus, Russia has Baksan, and Japan has Kamioka, the deepest current site in the US is the Soudan Laboratory, operated by the University of Minnesota, at a depth of 710 m. Access underground at Soudan is challenging because of the small lift that provides vertical access to that site.

One wonderful development for North America, however, is SNOLab, an expansion of the SNO experimental area in the Sudbury Mine, including both additional underground rooms and a significant surface support facility. This is the world’s deepest underground laboratory, two kilometers underground and providing 6010 mwe in overburden.

Some next-generation experiments could require 5000 mwe or more of overburden. Examples include certain next-generation dark matter, solar neutrino, and double beta decay efforts. Overburden is often important in experiments focused on measuring low-energy events: penetrating muons themselves can often be vetoed by ”turning off” the detector after a muon is detected. (Kamiokande, for example, has about a 10% deadtime due to this technique for background suppression.) But muons, in addition to producing prompt secondaries like knock-out neutrons, can also activate nuclei in the detector that, some time later, decay to produce a signal. In cases where there is a long delay before the induced activity is detected, conventional vetoing techniques can lead to an unacceptable deadtime. In such cases there is no alternative but great depth to remove the initiating muon events.

In other cases, backgrounds may be controllable at moderate depth, making great depth less important than other factors, such as the economies that come from ease of access: the ability to ”drive-in” large equipment and efficiently operate large experiments may be the priority. Both Gran Sasso and Kamioka, the world’s premier underground laboratories, are drive-in facilities at moderate depth.

Of local interest is the fact that the nation’s deepest transportation tunnels are here in Washington State: the parallel Cascade and Pioneer tunnels run under Stevens Pass, through the Mt. Stuart batholith, reaching a depth of 1040m. Burlington Northern’s mainline route from Puget Sound ports to Chicago runs through the Cascade Tunnel. The Pioneer Tunnel is unused, and BNSF has expressed a willingness to make this site available as a horizontal-entrance, dedicated science laboratory. The ease of highway and railroad access opens up exciting possibilities for mounting large neutrino experiments, etc.

The relevance to the present discussion is the importance of being able to calculate the muon flux at depth, folding the energy and angular spectrum at the surface with the irregular topography of Stevens Pass. A UW physics grad student, Kregg Philpott, has done
\[
\begin{array}{ccc}
E_\mu \text{ (GeV)} & R \text{ (1000 mwe)} & \alpha \text{ (10}^{-6} \text{ MeV cm}^2/g) \\
10 & 50 & 2.19 \\
100 & 410 & 2.74 \\
1000 & 2450 & 6.60 \\
10000 & 6090 & 46.43 \\
\end{array}
\]

Table 2: From Gaisser and Stanev: the calculated ranges R and energy losses b are both sharply dependent on the muon energy, and lead to a systematic hardening of the muon spectrum as one goes underground.

such calculations. The resulting contours of the muon flux under the Steven Pass’s Cowboy and Big Chief Mountains is shown in Fig. 8, for a horizontal slice at the Pioneer tunnel’s elevation. This tunnel proves to be at just the right place for convenient access to the point of greatest overburden, under Cowboy Mt. The resulting flux, \(2.07 \times 10^{-7}/\text{cm}^2\text{sec}\), is about 90% that at Kamioka (\(2.28 \times 10^{-7}/\text{cm}^2\text{sec}\)). Thus there is the prospect of establishing a laboratory in this state that would be very comparable to Kamioka. Kamioka has demonstrated the utility of such an intermediate-depth laboratory for large-scale experiments detecting solar neutrinos, nucleon decay, atmospheric neutrinos, and supernova neutrinos.

While we have discussed going deep underground to find an environment sufficiently clean to do neutrino physics, there are some absolute limits to what can be achieved. Atmospheric neutrinos provide a underground source of high-energy muons and electrons that does not attenuate: these are the muons that the energetic atmospheric neutrinos produce as secondaries. As Figure 9 shows, at a depth of about 10 km mwe (3.5 km of rock) these become a constant background that is not reducible by going further underground. It also follows that upward going muons (or electrons, though they have a shorter range) in deep detectors thus can be used as a signal of neutrino reactions in the rock below. Figure 10 is a reminder of our earlier discussion describing how these neutrino fluxes were exploited to probe neutrino oscillations, through the muons and electrons they produce in underground detectors.

Given that we have discussed so many aspects of the terrestrial neutrino flux, including the changes induced by neutrino oscillations, it is amusing to display the local neutrino spectrum in its entirety in Figure 11. The atmospheric neutrinos, despite their importance due to their high energies and larger cross sections in matter, do not appear on the graph because their fluxes are so low. Two sources we have not discussed in detail are the geoneutrinos, produced from terrestrial radioactivity and perhaps recently seen in KamLAND, and the thermal flux (\(\sim \text{keV}\)) of solar neutrinos of all flavors, generated in our sun from neutral current processes, analogous to those we discussed (at higher energies) in the context of supernovae cooling.

8.6 The highest energy cosmic rays and the GZK cutoff
Some of the most curious observations in cosmic ray physics have to do with the highest energy cosmic rays. A number of new instruments, such as the Fly’s Eye, the Pierre Auger,
Figure 8: The cosmic ray muon flux under Cowboy Mt., Stevens Pass, at the 743 m elevation of the Pioneer Tunnel. Calculation done by Kregg Philpott.
Figure 20.5: Vertical muon intensity vs depth (1 km.w.e. = 10^5 gc m^{-2} of standard rock). The experimental data are from: #06: the compilations of Crouch [32], #03: Baksan [33], f: LVD [34], v: MACRO [35], #04: Frejus [36]. The shaded area at large depths represents neutrino induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.

Contained and semi-contained events reflect neutrinos in the sub-GeV to multi-GeV region where the product of increasing cross section and decreasing flux is maximum. In the GeV region the neutrino flux and its angular distribution depend on the geomagnetic location of the detector and, to a lesser extent, on the phase of the solar cycle. Naively, we expect \( \nu^\mu / \nu^e = 2 \) from counting neutrinos of the two flavors coming from the chain of pion and muon decay. This ratio is only slightly modified by the details of the decay kinematics, but the fraction of electron neutrinos gradually decreases above a GeV as parent muons begin to reach the ground before decaying. Experimental measurements have to account for the ratio of \( \bar{\nu} / \nu \), which have cross sections different by a factor of 3 in this energy range. In addition, detectors generally have different efficiencies for detecting muon neutrinos and electron neutrinos which need to be accounted for in comparing.
Figure 1: The SuperKamiokande atmospheric neutrino results showing excellent agreement between the predicted (blue lines) and observed electron-like events, but a sharp depletion in the muon-like events for neutrinos coming from below, through the earth. The results are fit very well by the assumption of $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing (red lines).

Figure 10: The SuperKamiokande atmospheric neutrino results – which exploited the fact that penetrating neutrinos produce an irreducible flux of electrons and muons at depth.
FIG. 4. Natural neutrino sources. The terrestrial $\bar{\nu}_e$ flux and continuous flux of extragalactic supernova neutrinos of all flavors are from Krauss et al. [12]. The solar (fusion) $\nu_e$ flux is the standard solar result of Bahcall et al. [11]. The thermal solar neutrinos are for a single flavor. The spectrum contains a great deal of information on the temperature distribution within the sun. These remarks are made because the most likely opportunity for measuring the thermal neutrino spectrum is a process that depends on flux density, not on total flux, and which samples that flux at a precise energy, the resonant reaction $\bar{\nu}_e + e^- + (A, Z) \rightarrow (A, Z-1)$. (23) This reaction has been discussed previously in connection with terrestrial $\bar{\nu}_e$ sources [12]. Cross sections can be large in high-Z atoms, where the electron overlap with the nucleus is favorable. Because nuclear level widths are very narrow, this process samples the $\bar{\nu}_e$ flux density at a discrete energy. The are several possible candidate transitions with energies between 2 and 20 keV. (One that has been studied in connection with neutrino mass measurements is the decay of long-lived $^{163}$Ho to $^{163}$Dy, which has a positive q-value of less than 3 keV: either a neutrino mass or $\bar{\nu}_e$ inducement of electron capture alters the atomic orbits that participate in the capture.) The heavy-flavor neutrino flux also contains interesting information: if the existence of this flux were established, it would immediately impose kinematic mass limits of $\sim 1$ keV on $\nu_\mu$ and $\nu_\tau$. Unfortunately there is no obvious possibility for measuring these species. The problem could well prove as difficult as in the case of the cosmic microwave neutrinos, where existing experimental bounds exceed the expected flux by about 15 orders of magnitude [14].

Figure 11: The fluence of neutrinos at earth, ranging from cosmic background neutrinos to those produced by high-energy cosmic ray interactions in the atmosphere. From Haxton and Lin.
and the AGASA detectors, are designed with sensitivity to ultrahigh-energy cosmic rays. For example, the Fly’s Eye uses air fluorescence to detect UHE cosmic rays. An extensive air shower is generated when a primary cosmic ray interacts with the atmosphere. This is imaged using the fluorescence light produced by excitation of the nitrogen molecules by the secondaries in the extensive air shower. The shape of the shower allows the experimenters to reconstruct the energy of the primary. It also may provide some information on composition. The Fly’s Eye can provide stereo information on the developing shower because of detector arrays located 3.4 km apart.

The rare high energy events show some structure, particularly around $10^{19}$ eV, where the spectrum flattens from a slope of about -3.0 to one of about -2.6. Furthermore, both of the major groups have seen events above the Greisen-Zatsepin-Kuzmin cutoff of about $10^{20}$ eV. There are now tens of such events extending up to about $10^{21}$ eV (see Figs. 12 and 13).

The cosmic medium is filled by background radiation of relic photons, left over from the back bang and noninteracting since the time electrons and nuclei recombined to form atoms. Their typical energy is about $10^{-3}$ eV. We consider the propagation of a high energy proton through this medium.

Let $p_\mu = (\epsilon, \vec{p})$ be the photon four-momentum. Then $|\vec{p}| = \epsilon$. Let $P_\mu = (\omega, \vec{P})$ be the proton four-momentum. We evaluate in the center-of-mass

\[(P^\mu + p^\mu)(P_\mu + p_\mu) = (\omega + \epsilon)^2 = \epsilon_{CM}^2\]

which we recognize as the square of the center-of-mass energy. Note that if $\epsilon_{CM}$ exceeds

\[m_\pi + M_N\]

then clearly the reaction

\[\gamma + N \rightarrow \pi + N\]

can occur, degrading the nucleon energy. But the center-of-mass energy is a Lorentz invariant quantity, so it can be evaluated in the laboratory frame

\[\epsilon_{CM}^2 = M_N^2 + \omega \epsilon - \vec{P} \cdot \vec{p}\]

As the cosmic background photons are moving in all directions, we are free to maximize the RHS by taking $\cos \theta \sim -1$. Noting that the incident nucleon is highly relativistic

\[\left(\epsilon_{CM}^{max}\right)^2 \sim M_N^2 + 2\omega \epsilon\]

Thus the requirement for photoproduction is $\epsilon_{CM}^{max} \gtrsim m_\pi + M_N \Rightarrow$

\[\omega \gtrsim \frac{m_\pi^2 + 2M_N m_\pi}{2\epsilon}\]
Figure 20.9: The all-particle spectrum: reference sources are given in Fig. 20.10. The shower size $N_e$ and primary energy $E_0$ are only related in an average sense, and even this relation depends on depth in the atmosphere. One estimate of the relation is $E_0 \sim 3.9 \times 10^6$ GeV ($N_e/10^6$). For vertical showers with $10^{14} < E < 10^{17}$ eV at 920 g cm$^{-2}$ (965 m above sea level).

Because of fluctuations, $N_e$ as a function of $E_0$ is not the inverse of Eq. (20.13). As $E_0$ increases the shower maximum (on average) moves down into the atmosphere and the relation between $N_e$ and $E_0$ changes. At the maximum of shower development, there are approximately 2/3 particles per GeV of primary energy.

Detailed simulations and cross-calibrations between different types of detectors are necessary to establish the primary energy spectrum from air-shower experiments [52,53]. Figure 20.9 shows the “all-particle” spectrum. In establishing this spectrum, efforts have been made to minimize the dependence of the analysis on the primary composition. In the energy range above $10^{17}$ eV, the Fly’s Eye technique [71] is particularly useful because it can establish the primary energy in a model-independent way by observing most of the longitudinal development of each shower, from which $E_0$ is obtained by integrating the energy deposition in the atmosphere.

Figure 12: The all-particle cosmic-ray spectrum showing approximately 20 events measured between $10^{19}$ and $10^{21}$ eV. An expanded spectrum is also shown. From Gaisser and Stanev.
Figure 13: A comparison of the HIRES and AGASA high-energy cosmic ray events. The latter data set tends to show more events at or above $10^{20}$ eV.
\[ \sim 1.4 \cdot 10^{20} \text{eV} \]

This results in a mean free path for protons of about \(10^8\) light years for protons at \(\sim 10^{20}\) eV or higher energies, a distance substantially smaller than the horizon. Thus if the origin of such cosmic rays is all of extragalactic space, there should be a very sharp cutoff in the cosmic ray flux at about this energy. This is called the Greisen-Zatsepin-Kuzmin cutoff, and is shown in the figure. Yet the very high energy events from AGASA show no evidence for any such cutoff.

There are some disagreements among groups about how well energies are reconstructed. But if the results are correct, it is an interesting puzzle. Fairly mundane solutions have been offered, such that these high energy events are exclusively nuclear (CNO elements and then iron), which can achieve higher energies at lower velocities. It has been suggested that the events are secondaries from the collisions of still higher energy neutrinos. However this requires new physics in that the Standard Model predicts a declining neutrino cross section above the Z mass that would not be sufficient to produce the needed event rate, it is thought.

It could be that ultrahigh energy cosmic rays both above and below the GZK cutoff are of relatively local origin. That would avoid the puzzle; but it would raise a new question of what confines the cosmic rays if they are extragalactic but somehow produced primarily in a local region about us. Perhaps we are somehow near some remarkable local source or sources: our position in the cosmos is special. All of this is intriguing.

The nuclear solution may not evade all of the problems if experiments find that the spectrum runs beyond \(10^{21}\) eV, as other types of GZK cutoffs effect nuclear species. At a center-of-mass energy considerably below pion production threshold, nuclei can absorb (in their rest frame) a photon of energy \(\sim 20\) MeV, resulting in photodistintegration. This leads to a GZK cutoff for iron nuclei of

\[ \sim 10^{21} \text{eV} \]

8.7 Gamma rays
The properties of the earth’s atmosphere divides gamma ray astronomy into two halves. From the ultraviolet to gamma rays of energy \(\sim 20\) GeV the atmosphere is opaque. Thus observations in this energy range must be done with instruments mounted in satellites or carried by balloons. The ease of detecting the radiation generally goes up with energy, but the strengths of typical astrophysical sources go down. The net result is that one can do a lot over this range: this motivated the design of the four instruments on board the Gamma Ray Observatory. For gamma rays above 20 GeV, interactions in the atmosphere produce showers that can be observed either by the Cerenkov light produced by the secondaries or, at high altitude, by direct detection of the secondaries. Of course, observations can also be (and are) made by space-bound detectors, too.

Many of the concerns of this field are driven by instrumental issues (so it would be better to have an experimentalist giving this talk). The central issues are rather obvious:
• Producing detectors with greater sensitivity. The dynamic range of existing detectors - the gap between the brightest nearby sources such as the Crab and the faintest detectable sources - is typically about a factor of 100. Thus the situation is equivalent to being able to see no stars fainter than the 5th magnitude. Improvements in sensitivity can thus greatly extend the horizon of our observations, while also allowing much more detailed spectral studies of known bright sources. Greater sensitivity can be achieved with great collection areas and by reducing ambient backgrounds. The push towards greater size is clearly an expensive challenge given the necessity for observing outside the atmosphere.

• Enhancing spectral resolution. This includes both enhanced spectral resolution and enhanced spatial resolution, the latter required to better identify sources.

• Enhanced temporal covering and resolution.

Examples of why such extended capabilities are important are provided by the GRO instruments. For example, BATSE - the Burst and Transient Source Experiment - was designed as an all-sky monitor with sharp timing capability. This proved decisive in demonstrating that gamma ray bursts are distributed approximately isotropically. This detector also led to the discovery of new pulsars, x-ray novae, and the identification of one soft gamma ray repeater. Likewise another GRO instrument EGRET - the Energetic Gamma Ray Experiment - was able to correlate high energy gammas with the lower energy bursts detected by BATSE. It also measured high energy gammas from active galaxies.

8.8 Nuclear Gamma Rays

We have touched on this theme before, but here I’d like to gather together several examples of what is becoming possible. One of these examples is $^{26}$Al, which has a 720,000 y lifetime for decay to $^{26}$Mg. The decay of the $5^+$ ground state populates the first two excited states of $^{26}$Mg, which are $2^+$ states with energies of 2.938 and 1.809 MeV. The latter state is populated 97% of the time, so the primary signature is a 1.809 MeV $\gamma$. The 2.938 MeV state decays to the 1.809 MeV level, so a small number of 1.129 MeV $\gamma$s are also produced. The primary site for producing $^{26}$Al is thought to be Type II and IIb supernovae. Additional aluminum may come from the winds of very massive stars. COMPTEL has produced a galactic map of the 1.809 MeV $\gamma$s. That map differs from higher energy ($\sim$ 100 MeV) maps in that there is marked clumpiness to the production, including intense sources associated with Cygnus, Vela, etc. This map is interpreted as an indicator of recent supernova activity. The conclusions drawn from such a map are clearly model dependent because one obtains an angular distribution but no spatial depth information. But under the assumption that the entire galaxy is contributing in the expected way, one deduces a recent supernova rate of $3.4 \pm 2.8$/century. The model dependence also includes the uncertainty in the aluminum production per event. The attribution of the total flux to the Al injection rate of massive stars yields an upper bound on the recent star formation rate of $5 \pm 4 \, M_\odot$ per year. This calculation, of course, requires not only a model of the Al production per supernova, but also a model of the range of stellar masses that undergo core collapse and a model for the
distribution of stars with mass (populations roughly decline exponentially with an exponent of about -2.35).

In a similar way, $^{44}$Ti decay proceeds with a $\sim 60$ year half life to the ground state of $^{44}$Sc, which in turn electron captures to $^{44}$Ca. The order of the states in Sc is $2^+$ (gs), $1^-$ (68 keV), and $0^-$ (146 keV). The decay feeds the second excited state 98% of the time, which then decays through the $1^-$ state to the ground state, producing $\gamma$s of 78 and 68 keV. The subsequent decay to $^{44}$Ca has a 4 hour lifetime and produces a 1.157 MeV $\gamma$, as the $2^+$ first excited state of $^{44}$Ca is populated 99% of the time. The $\sim 100$ keV line for the source Cas A is within the detection abilities of OSSE, while the 1.157 MeV line can be seen by COMPTEL.

Various types of supernovae are thought to produce $^{44}$Ti, including both types I and II. As in the case of the $^{26}$Al line, the galaxy is effectively transparent to the produced $\gamma$ ray, so the detection provides a measure of the very recent supernova rate free from worries about obscuration. One expects to have a sensitivity with COMPTEL to nearby supernovae occurring within the past 1000 years, or 15 half lives. Given a supernova rate of some several per century, it is clear that the distribution should be from quite localized sources, representing recent events. Typical productions of $^{44}$Ti from supernovae are, according to modelers, on the order of $10^{-4}$ $M_\odot$ per event.

The youngest known galactic supernova remnant is Cas A, noted optically by John Flamsteed in 1680. COMPTEL reported the observation of $^{44}$Ti $\gamma$s from Cas A in 1994. The very recent report of a survey extending over a six-year period beginning in 1991 found only one additional source, identified with a young supernova remnant not observed either optically
or in the radio. The source is located in the direction of the Vela constellation. Constraints on the doppler broadening of the 1.16 MeV line limits the velocity of the ejecta to no more than 19000 km/sec. The COMPTEL results are confirmed by ROSAT xray data of the vela region, which found a shell-type supernova remnant at the same location. The shell temperature is on the order of several keV, which also indicates a young remnant. Finally, COMPTEL previously saw $^{26}$Al in this region, attributing this to the known Vela supernova remnant. However the centroid of that distribution has been argued to better fit the new supernova remnant. Modelers are currently engaged in arguments about the nature of the progenitor, using both the ejection velocity bound and the $^{44}$Ti yield to bound models. One possibility is a core-collapse supernova of a massive star that had previously lost its hydrogen envelope. It has been claimed that a supernova at this distance (100-300 pc, derived from the Ti $\gamma$ flux and age estimates of 600-1100 years based on the expansion velocity) could have been as bright as the moon, leaving an interesting question as to why it was not observed.

Finally, there have been recent papers suggesting that future generations of gamma ray detectors might see $\gamma$s in the energy range of 100-700 keV associated with elements specific to the r-process. Establishing a correlation between such $\gamma$s and known supernova remnants could thus establish the r-process site and, potential, constrain the total r-process production per site. One of the candidates, $^{126}$Sb, has a 144,000 year lifetime, easily long enough to allow a galaxy survey. It produces lines at 415, 666, and 695 keV. The proposed detector ATHENA possibly could detect $^{126}$Sb lines from Vela.

8.9 Astrophysics of High Energy Gammas

EGRET succeeded in identifying on the order of 100 high-energy gamma ray sources associated with active galaxies and characterized by nonthermal spectra. Such "blazars" are highly variable and are bright radio sources. The radio structure consists of knotty jets moving outward at high velocities. The luminosity in gamma rays can exceed that from other wavelengths by up to two orders of magnitude. The variability of the emission can be fast, less than a week. The density of high energy gammas at the source are sufficient that photon-photon pair production would keep them trapped, unless the gammas are highly beamed, as in a relativistic jet. Thus the hope is that the gamma ray spectrum can yield information on the nature of the jet and of the acceleration processes occurring there. It is thought that the gamma rays may originate from a region of the jet closer to the central engine, than in the case of the radio emission.

A few blazars have been observed producing very high energy gamma rays, up to TeV scales. One, Markarian 421, was measured in the TeV range by the Whipple Observatory, which detects Cerenkov radiation from air showers. It was not seen at GeV energies by EGRET. The high energy flare had a rise time of about two days. One day after the flare commenced this source was seen in the X-ray. Both of these signals differ from typical blazars in their higher energies: most blazars have lower energy gamma and low-energy radiation that does not extend into the x-ray. The interpretation is that blazars accelerate electrons to high
energies, which then radiate soft synchrotron radiation and hard gammas by inverse Compton scattering. Markarian 421 is thus exceptional in the energies to which it accelerates electrons, accounting for the higher energy of its x-ray/gamma emission.

Markarian 421, which was first observed in May, 1994, is not unique. The second closest blazar of this type, Markarian 501 (z=0.034), was seen in 1997. It flared to become the brightest TeV source in the sky, outshining the Crab Nebulae by an order of magnitude. The periods of flaring lasted a few days. The elevated activity spanned a period from about March through June. The high energy spectrum (observed by Whipple) was flat from below a TeV to at least 10 TeV. The x-ray cutoff in Markarian 421 is about 1 keV; in Markarian 501 it is above 100 keV. As in 421, it is assumed that this spectrum comes from relativistic acceleration of electrons along a jet closely aligned with our line of sight.

What does this tell us about the electron energies? First, the plasma in the jet is moving towards us, boosting the energy of the emitted gammas, relative to the jet rest frame. The Doppler factor is

$$D = \frac{\sqrt{1 - v^2/c^2}}{(1 + z)(1 - v \cos \theta/c)}$$

where $\theta$ is the observation angle relative to the jet axis. This is the standard relativistic Doppler shift corrected by the redshift. The observed energy of the gamma rays is

$$E_{\text{max}} \sim D\gamma m_e c^2$$

where $\gamma m_e c^2$ is the maximum energy of the electrons in the jet rest frame. The Doppler factor also appears in the calculation of the photon density in the blob, and thus of the blobs opacity to high energy $\gamma$s. The argument goes as follows: if $\Delta t_{\text{obs}}$ is the fastest observed TeV gamma ray flare variability, then the radius of the blob emitting the photons must be less than

$$\sim cD\Delta t_{\text{obs}}$$

Thus a larger D means a lower photon density. From this one concludes $D \gtrsim 30$. Since the highest energy gammas from Markarian 501 is about 20 TeV, one derives for the maximum energy of electrons in the jet frame

$$\gamma m_e c^2 \sim 0.65\text{TeV}$$

Since the maximum electron velocity is now known, one can deduce the magnetic field in the jet required to produce synchrotron radiation with a maximum energy of 200 keV. That yields

$$E_{\text{max}} \propto DB\gamma^2 \Rightarrow B \sim 0.7G$$

where B is the field in the jet rest frame. Other aspects of the blazar dynamics - such as the physics responsible for the short timescale of the flares - is less clear.
Another exciting result involving high energy $\gamma$s are the gamma ray burst observations of EGRET. While the vast majority of the bursts are seen by BATSE, on the order of 10% of the events produce spectra that extend into EGRET's range of above 30 MeV, typically producing about five counts. The most dramatic event was that of February 17, 1994, in which the high-energy gamma ray emission appeared to extend for an hour or more beyond the sub-MeV emission detected by BATSE. The highest energy event was at 18 GeV and occurred almost an hour after the BATSE observations ended.

These high energy tails place a lot of constraints on gamma ray burst models. Since high energy gammas were also seen early in the burst, there must be high-energy particle acceleration simultaneous to the keV emission. The lack of attenuation of high energy $\gamma$s from $\gamma-\gamma$ pair production off lower energy $\gamma$s place a particularly strong constraint on the source and on models involving beaming.

Finally, a third interesting source of high energy $\gamma$s are both isolated and binary pulsars. Gamma ray emission can be very strong, representing 10% or more of the spin-down energy of some pulsars. There is relatively little consensus on the mechanism or even the precise site of the gamma ray production (neutron star surface? accretion disk? etc?)

Centaurus X-3 is a well-studied high-mass accreting X-ray binary. EGRET measured a smoothly declining spectrum that extended from 100 MeV to its detection limit. Results have been reported from the Durham Mark 6 gamma ray telescope in the vicinity of a TeV: the flux is consistent with a linear extrapolation of the EGRET flux. Centaurus X-3 contains a 4.8s pulsar in a 2.1 day orbit about an O-type supergiant V779 Centaurus. The pulsar period has been shortening since its discovery almost 30 years ago, which is attributed to spin-up from matter accreting on the neutron star from the more rapidly rotating inner edge of its accretion disk. The EGRET GeV burst observations were pulsed in agreement with the X-ray period. Initial TeV gamma ray observations also indicated pulsation near the pulsar period and localized in But later measurements at high energy indicated unpulsed emission that one would then associated with radiation over an extended volume encompassing the orbit.

8.10 Gamma ray bursts

Gamma ray burst have been mentioned several times. Gamma ray bursts are short-lived burst lasting from a few milliseconds to several minutes. They are detected roughly once per day, from all directions in the sky. They represent tremendous energy, several hundred times brighter than a typical supernova (were they radiated in $4\pi$). They were originally detected in the 1960s by military satellites monitoring nuclear testing. They are not local, but originate at cosmological distances. In the past few years it has become clear they are associated (at least some of the time) with certain supernovae.

Recently fast-response telescopes - like NASA’s High-Energy Transient Explorer or the
Japanese Automated Response Telescope - have been able to view the gamma-ray burst area within a couple of minutes of the burst. The "afterglows" have been observed for on the order of an hour to a day after the burst – representing a lot of additional energy.

General ideas exist that gamma ray bursts are associated with fireball phenomena where tremendous energy and high velocities are produced in a region relatively free of baryons – to keep the gamma rays from thermalizing. The motion leads to a beaming of the burst, reducing the energy requirements but increasing the frequency of events (many of which are not beamed at earth and thus are not observed).

A specific idea is the hypernova. A massive star’s core collapses into a black hole. The black hole’s spin or magnetic fields may act like a slingshot, flinging material outward as a beamed blast wave or jet. The gamma rays are created when the blast wave collides with stellar material still inside the star. The gamma rays burst out of the star just in front of the blast wave. Behind the gamma rays, the blast wave pushes the stellar material outward.

Figure 15: A long-duration gamma ray burst event.
The blast wave then sweeps through space, colliding with gas and dust, producing additional radiation — progressing from less energetic gammas, to x-rays, to visible light, and to radio. This forms the afterglow, lasting perhaps up to days.