PHYC 581: High Energy Astrophysics
Fall 2018

Lecture 30:

12/03/2018

The High Energy Background

Not all of the high-energy activity in the cosmos is associated with unresolved point sources that are compact sources. In fact, the birth of high energy astrophysics goes back to the early 1900's when Victor Hess studied ionizing radiation near the surface of the Earth. Just as the compact objects form distinct sources of high-energy emission with characteristic spectra, so too are the various diffuse sources that should be considered separately.

Cosmic Rays

Direct observation of these particles is only possible with instruments in space or high-altitude balloons as they are shielded by Earth's atmosphere. The differential cosmic ray spectrum, shown on the next page, is a steeply falling function of energy with a power-law index of ~ -2.7 up to an energy of $\sim 4 \times 10^{15}$ eV (the first "knee"), which steepens further at higher energies.

At energies above 100 TeV, the showers of secondary particles created by interactions of cosmic rays with the upper layers of atmosphere are extensive enough to be detected from the ground.

The total cosmic ray energy density measured above the atmosphere is dominated by particles in the 1-10 GeV range. Below ~ 1 GeV, the intensities are correlated with solar activity pointing toward a solar origin. On the other hand, the cosmic ray

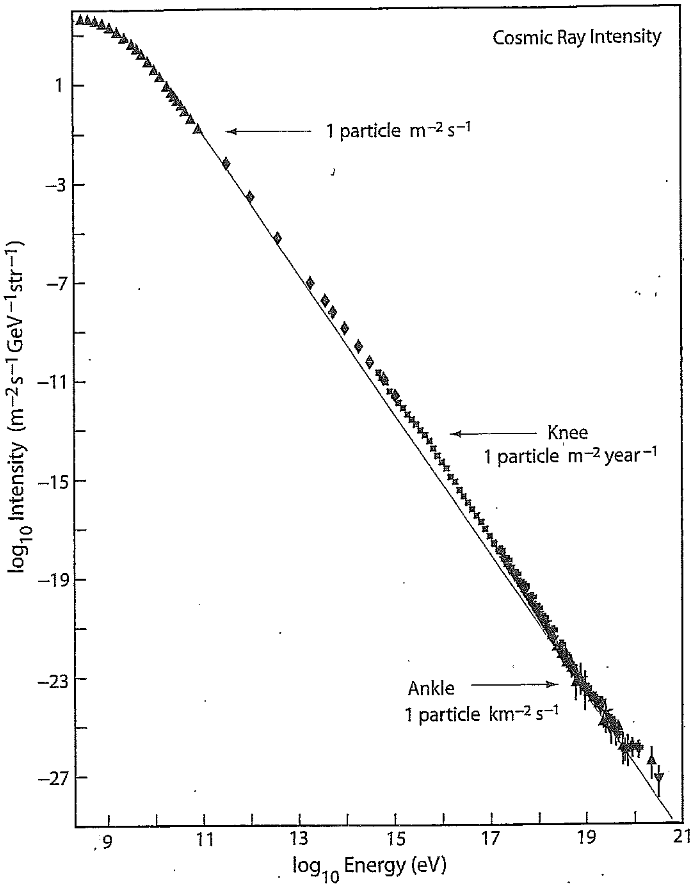


Figure 13.1 A compilation of the cosmic-ray all-particle spectrum observed over the whole range of energies accessible by the various experimental techniques now in use (see text). The distribution is roughly a power law over a wide range of energies, though comparison of the data to a single power law (the thin solid curve) reveals significant breaks at the "knee" (around 4×10^{15} eV) and, to a lesser extent, at the "ankle" (at $\sim 5 \times 10^{18}$ eV). Cosmic-ray particles with energies $> 10^{20}$ eV have also been detected, but the sources and the physical mechanism(s) responsible for producing such enormous energies are unknown. Current theories of cosmic-ray production generally fall into two main camps: "bottom-up" acceleration, in which charged particles are accelerated to high energies in supernova shocks, active galactic nuclei, powerful radio galaxies, or the strong electric fields generated by magnetized, rotating neutron stars; and "top-down" scenarios, in which energetic particles are created from the decay of more massive particles originating in the early universe. (From Bhattacharjee and Sigl 2000)

From "High-Energy Astrophysics" (page 304)

by Fulvio Melia

Princeton University Press 2009

flux at higher energies is anti-correlated with solar activity thereby pointing to an origin outside the solar system. According to conventional wisdom, the bulk of the cosmic rays below the knee are produced in supernova remnants. The knee is sometimes interpretted as a crossover between the galactic and extragalactic populations. Beyond ~ 10 EeV, the galactic magnetic fields would not be able to confince the cosmic rays within the galaxy.

The cosmic ray particles diffuse throughout the interstellar medium upon production and interact with gas along the way and produce secondary particles. The secondary to primary abundance ratio can be used to estimate the mean column density $N(E)$ that they traverse:

$$N(E) \simeq 6.9 \left(\frac{E}{2\cdot Z\ \mathrm{GeV}}\right)^{-0.6} g\,cm^{-2}$$

Here, Z is the mean charge of the cosmic ray and E is its energy. If $\tau_{res}(E)$ denotes the mean residence time of a cosmic ray particle with energy E in the galaxy, we have:

$$\tau_{res}(E) \simeq \frac{N(E)}{c\rho_{ism}}$$

Here, ρ_{ism} is the interstellar medium density and cosmic ray particles move relativistically. This implies that:

$$\tau_{res}(E) \simeq 7 \left(\frac{E}{2\cdot Z\ \mathrm{GeV}}\right)^{-0.6} \left(\frac{\rho_{ism}}{10^{-24}\ g\,cm^{-3}}\right)^{-1} \mathrm{Myr}$$

Assuming that the cosmic ray population is in equilibrium, the source must compensate the lost energy at a rate:

$$L_{cr} = \int d^3x\, dE\ \frac{E\, 4\pi\, J_{cr}(E)}{c\,\tau_{res}}$$

Here, $J_{cr}(E)$ is the cosmic ray intensity shown in the figure and the factor of 4π arises due to isotropic distribution. We therefore find:

$L_{cr} \sim 1.5 \times 10^{41}$ erg s^{-1}

This is ~10% of the estimated power output in the form of kinetic energy ejected by galactic supernovae. Thus, from an energetic point of view, supernova remnants could account for most of the cosmic rays. This is the main reason that it is though that cosmic rays up to the knee originate from first-order Fermi acceleration in the shocks between the expanding supernova ejecta and the surrounding medium.

For a given acceleration site, a maximum energy E_{max} can be achieved, which is limited by the acceleration time or the size of the site. Recall the Lorentz force under the influence of a magnetic field $\vec{B}$:

$$\vec{F} = q \frac{\vec{v}}{c} \times \vec{B}$$

Using the relativistic expression $\vec{p} = \gamma \underset{\substack{\downarrow \\ \text{(proton mass)}}}{m_p} \vec{v}$, and for $|\vec{v}| \simeq c$,

this gives:

$$\gamma m_p \left|\frac{d\vec{v}}{dt}\right| \simeq q|\vec{B}| \Rightarrow \gamma m_p \frac{|\vec{v}|^2}{r_{gyr}} \simeq q|\vec{B}| \Rightarrow \gamma \simeq \frac{qBr_{gyr}}{m_p c^2}$$

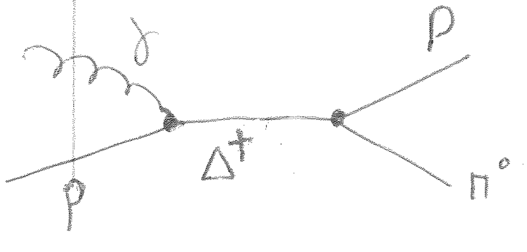
The magnetic field in the interstellar medium is $B \sim 10^{-6}$ G. With compression inside the shock, it may grow to $B \sim 10^{-5} - 10^{-4}$ G. The width of the shock in supernova remnants is $\sim 1-10$ pc. The maximum energy then is given by:

$$E_{max} \sim \gamma m_p c^2 \sim 6 \times 10^{15} \text{ eV}$$

This makes the case rather compelling for cosmic rays up to this energy have a galactic origin. Note that the same argument can be used to show that cosmic rays beyond EeV cannot be confined within the galaxy by the magnetic field of the interstellar medium. The extremely high energy cosmic rays must therefore (almost) certainly originate from outside the galaxy.

Current theories of extremely high energy cosmic rays are divided into two categories: (1) The "bottom-up" models, in which charged particles are accelerated from lower energies to the required higher energies, (2) The "top-down" models, in which the energetic cosmic rays are decay products of some superheavy relics from the early universe. In the bottom-up scenarios, the charged particles typically find it difficult to escape from the acceleration zone without losing most of their energy (except, perhaps, the powerful radio galaxies).

In any case, all extragalactic sources of cosmic rays are constrained by the so-called Greisen-Zatsepin-Kuzmin (GZK) cut-off. This is due to interaction of protons with the cosmic microwave background photons leading to pion production:



The cross-section for this process is large when the energy is at or above the mass of Δ^+. This happens when $E_\gamma E_p \sim (m_\Delta c^2)^2$. Since $m_\Delta c^2 \simeq 1.2$ GeV and $E_\gamma \sim 10^{-3}$ eV, we then find $E_p \sim 10^{20}$ eV.

Knowing the cross-section for this process, and the density of the cosmic microwave background photons, it turns out that ultra high energy cosmic rays (i.e., $E > 10^{20}$ eV) cannot originate from distances greater than 50 Mpc (with conservative estimates).

The top-down models may do better than the bottom-up ones in this respect. The candidate sources that could accelerate charged particles to energies $\gtrsim 10^{20}$ eV seem to reside at distances greater than 100 Mpc, and hence subject to the GZK cut-off.