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ASTROPHYSICS OF GALACTIC COSMIC RAYS*

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The Galactic Cosmic Rays contain a sample of matter from elsewhere in the galaxy. It is a relatively recent sample ($\sim 10^7$ years old) and contains information on the source material and conditions of confinement and transport in the galaxy. Unraveling the astrophysics of the cosmic rays has been underway for half a century, but major progress has been made in the last decades. The current state of our astrophysical knowledge of cosmic rays is reviewed in different energy regions, with particular attention to the implication of recent isotopic composition measurements at low energy. Extrapolating to higher energy delineates some of the experimental challenges facing the field in the future.

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1. Introduction

Galactic Cosmic Rays, those ubiquitous high energy particles that fill the disk of our galaxy and extend far beyond the disk into the halo, have been studied for almost a century. Yet, much remains to be learned about the cosmic ray beam itself, particularly its source(s) and acceleration mechanism(s), and about the role of cosmic rays in both galactic and extra-galactic astrophysics. We have learned much as evidenced by comparing some of the various monographs on the subject [1–7] covering nearly 40 years.

Viewed in a galactic context, the cosmic rays are a relativistic gas of ionized particles, tied to the galactic magnetic field. Together with the field, the cosmic rays provide the outward pressure to balance the gravitational pressure, thereby holding the galaxy in approximate dynamical balance. The galactic magnetic field is anchored in the matter within the disk. Cosmic rays propagating along magnetic field lines must interact with the instellar

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matter, producing some of the ionization in the interstellar medium (ISM) and leading to secondary particles (hadrons, leptons, photons). In particular, such interactions produce gamma rays which become a tracer of the distribution of the galactic cosmic rays. The same is true of neutrinos, and neutrino astrophysics is rapidly becoming one of the new branches of high energy astrophysics.

Cosmic ray electrons produce radio synchrotron radiation in the galactic magnetic field, and the synchrotron radiation has been used as another tracer of cosmic rays. The extended radio synchrotron halo observed in most galaxies attests to the presence of cosmic ray electrons far away from the disk. This also demonstrates that high energy cosmic rays are present in most, if not all, galaxies. Moreover, we see evidence for cosmic rays in the meteoritic record going back billions of years, so cosmic rays are a, more or less, permanent component of our galaxy.

The twentieth century has witnessed a revolution in astronomy and astrophysics. Instead of studying our universe through a few 'windows', optical and radio astronomy, today we have access to 'windows' extending from radio through the infra-red to high energy gamma rays. We can bring the power of multi-wavelength observations to bear upon a variety of astrophysical problems, often with amazing advances in knowledge. However, to the astronomical windows should be added the additional information provided by the Galactic Cosmic Rays. It is evermore evident that we live in a high energy universe and accelerated charged particles — Cosmic Rays — are a major part of the high energy phenomena we observe.

Following a brief historical overview, this paper reviews our understanding of the galactic cosmic rays, from low to high energy. Outstanding questions are addressed as well as prospects for the future.

2. Historical overview

The discovery of cosmic rays is usually attribute to Victor Hess who, in 1912, ascended in a balloon to an altitude of about 5 km, while recording the intensity of ionizing radiation. His observation of increasing intensity with altitude was confirmed by Kolhörster the next year in a flight to an altitude of about 9 km, and led credence to the idea that the radiation was coming from outside the Earth's atmosphere. It would take 20 more years before discovery of the latitude effect which proved that the primary cosmic rays were charged particles and not gamma rays and several additional years before the discovery of the East–West effect proved that the primary particles were positively charged, presumably high energy protons.

Meanwhile, rapid development of cloud chambers clearly showed the interactions of cosmic rays and the production of showers, and this led to the development of cascade theory, which remains the basis for describing atmospheric showers. Using a cloud chamber in a magnetic field Anderson discovered the positron. Along with the development of cloud chambers and Geiger tube arrays, a new method of observing charged particles was being perfected — the nuclear emulsion in which the tracks of charged particles could be recorded, permanently, in the photographic medium. The nuclear emulsion technique led rapidly to the discovery of mesons and other elementary particles and ushered in the first era of Astroparticle Physics — an astrophysical 'beam', cosmic rays, providing discoveries in particle physics. This was the main focus of cosmic ray research for over a decade until the advent of the cyclotron moved particle physics into the new accelerator laboratories.

Balloon flight technology continued to improve with the designs of zero-pressure balloons by Winzen and collaborators, and these balloons could carry scientific instruments to 20–25 km in altitude. On one such flight in 1948, carrying cloud chambers and nuclear emulsions, tracks of helium and heavier nuclei were observed. Thus, the cosmic ray beam became a sample of extra-solar matter available for astrophysical study. This ushered in the era of cosmic ray Astrophysics, in which we are still engaged. In the ensuing decades, electrons (both negative and positive) were discovered in the cosmic rays at a level of $\sim 1\%$ of the protons and primary x-rays and gamma-rays were observed at the top of the Earth's atmosphere. High energy astrophysics had 'come of age'!

One should also note the discovery of elements beyond the iron peak ($Z \geq 29$) in the cosmic radiation. This ultra-heavy component extends all the way through the actinide elements. This discovery revealed that the cosmic rays were not only a sample, but a relatively complete sample, of matter from beyond our solar system. On another front, many investigators were studying the cosmic ray induced showers produced in the atmosphere with large ground based arrays of particle detectors. These air shower measurements traced the all-particle energy spectrum and showed that the particle spectrum extended to enormous energies (circa 10^{20} eV) well beyond anything achievable in terrestrial accelerators.

Understanding Galactic Cosmic Ray Astrophysics involves two separate paths. First, we need to investigate the astrophysical questions involved in the cosmic rays themselves, *e.g.* sites of origin, matter sample, acceleration mechanism(s). Second, we can utilize the cosmic rays as astrophysical probes of processes in the galaxy or in our heliosphere.

3. Characterizing cosmic rays

There are three main parameters that characterize the galactic cosmic rays: composition, energy spectra and anisotropy. The cosmic rays are observed to be highly isotropic, arriving equally from all directions. This is attributed to their propagation in turbulent galactic magnetic fields which remove directional information. Thus, it is only at the highest energies, where the particle gyro-radius is of the order of the dimensions of the galactic disk, that we might anticipate observing a galactic anisotropy.

The cosmic ray energy spectrum covers an enormous range in energy, about 14 decades, over which the intensity falls by an even greater factor of 10^{32-34}, and therein lies the problem. No single technique can cover such large energy and intensity ranges, as illustrated in figure 1. For this review, we divide the overall energy spectrum into several intervals. Low energy includes the region accessible to satellite and balloon observations and corresponds, approximately, to the energy range up to the peak in the spectrum, near 1 GeV/nucleon. The "high" energy region covers the next three decades up to ~ 1 TeV/nucleon and is studied largely by balloon experiments, large space experiments and high altitude mountain facilities. The next 4–5 decades can be termed the "very high" energy region in which there is a mixture of ground and balloon based investigations. The VHE region contains the 'knee' in the spectrum, which is discussed later. Finally, UHE (ultra high energy) cosmic rays encompass the remainder of the spectrum, up to 10^{20-21} eV. The UHE region is largely the provenance of the extensive air shower technique.

Composition is perhaps the richest of the parameters characterizing the cosmic rays. In addition to primary particles (those that originate at the source), the composition involves all of the secondary species, including both matter and anti-matter. It is the secondary species that carry most of the information about cosmic ray transport in the galaxy. In addition to elements, isotopes of many species can be studied. Finally, there is the possibility that new or exotic forms of matter hide within the cosmic ray beam. Many 'new' types of particles or interactions have been reported, but none has been verified. Nevertheless, it is the search for such 'new physics' that helps to drive cosmic ray science.

An assessment of the state of our knowledge of cosmic ray composition in the four energy ranges defined above is given in Table I. Clearly we have the most complete information on composition in the low energy region and the challenges for the future are to (a) obtain better information in the UH ($Z \geq 29$) charge interval, (b) extend isotopic measurements into the High Energy range, and (c) obtain better elemental information both at VHE and for the UHE air showers.

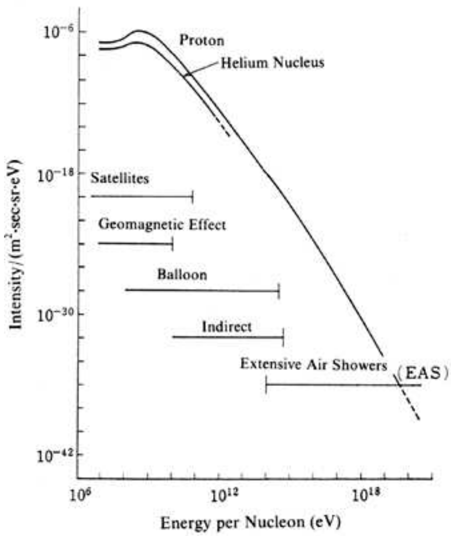

Fig. 1. Schematic representation of the cosmic ray energy spectrum and modes of measurement. (Adapted from [3].)

TABLE I

Cosmic ray composition

Component	Low energy	High energy	Very high energy	Ultra-high energy
anti-nuclei	upper limits	upper limits		
anti-protons	$\surd$	$\surd$		
positrons	$\surd$	$\surd$		
electrons	$\surd$	$\surd$	$\surd$	
All-particle	$\surd$	$\surd$	$\surd$	$\surd$
$Z - 1, 2$	isotopic	some isotopic	elemental	groups
$Z = 3$–5	isotopic	elemental	group	
$Z = 6$–9	isotopic	elemental	even-Z	group
$Z = 10$–19	isotopic	elemental	group/even-Z	
$Z = 20$–28	isotopic	elemental	group	group
$Z = 29$–40	even-Z	even-Z		
$Z = 41$–59	even-Z	even-Z		
$Z = 60$–72	groups	groups		
$Z = 73$–83	even-Z	even-Z		
$Z > 83$	actinide group	actinide group		

The existence of detailed elemental composition extending to VHE, and to very high charge, is owed to the development of Cherenkov and transition radiation detectors for balloons and satellites [8–10]. Similarly, the triumph of achieving isotopic resolution through the iron peak at low energy is due largely to the development of high precision lithium drifted Silicon detectors and associated electronics for space flight. This began in the 1960's and culminated in the Advanced Composition Explorer (ACE) mission [11] whose cosmic ray instruments have delivered much of the highest quality, high statistics data now available.

Advances in measuring anti-matter, and light nuclei isotopes, have resulted from the development of (superconducting) magnet spectrometers for balloon flights [12–15]. This technology is currently transitioning to space on coming missions. One should also note the development of solid state nuclear track detectors, particularly the glass detectors which were exposed on the MIR station and returned data on $Z > 70$ cosmic rays [16].

Astrophysical interpretation of the measured composition requires the relative abundances at the source(s) of the cosmic rays. This necessitates unfolding the secondary contributions from each element or isotope. There are a number of propagation models that have been used, but common to all is (a) the mean amount of material traversed by the particles, (b) the shape of the distribution of pathlengths followed by the cosmic rays and (c) the mean confinement time of the particles. Of course, one also requires a set of cross sections for secondary particle production from the interaction (fragmentation) of the primary nucleus. (One of the major achievements over the past three decades has been the steady progress in the measurement of these needed cross sections, coupled with refinement of the predictive models used to calculate any un-measured cross sections [17].) The needed parameters can be obtained from the secondary to primary ratios measured in the cosmic rays. For example, the B/C ratio, figure 2, is usually employed to determine the mean amount of material, and, coupled with the sub-Fe/Fe ratio, indicates an exponential distribution of pathlengths. Radioactive secondaries provide the means to determine the confinement time. First among these is ^{10}Be, but the new ACE data [18] allows ^{26}Al, ^{36}Cl and ^{54}Mn to be employed, as well, to determine a mean confinement time of about 20 million years. With these parameters one can use diffusion, leaky box, or weighted slab models [19, 20] to determine the needed source abundances. (In practice, a set of source abundances is assumed, and used to calculate the observed abundances. The source abundances are iterated until agreement with the data is obtained.) The results are relatively model independent, provided the calculations reproduce the secondary to primary ratios. (Failure to reproduce the B/C ratio, for example, has led to the demise of many propagation models.) It should be noted that, in the low energy region, it is necessary to correct for the effects of solar modulation on the calculated spectra and ratios. The curves in figure 2, for example, are corrected for a modulation level of 500 MV.

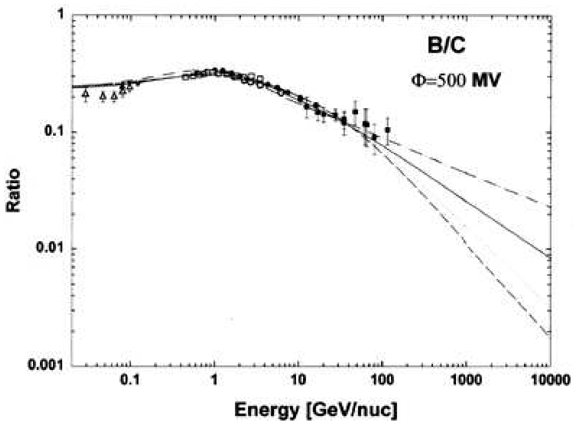

Fig. 2. Compilation of measurements of the B/C ratio as a function of kinetic energy. Curves are fits from different propagation models extrapolated to high energy.

The secondary to primary ratios decrease with increasing energy beyond the peak at about 1 GeV/nucleon. This shows that galactic propagation is an energy dependent process, with the amount of material traversed by the particles decreasing with increasing energy. This has been interpreted as the particles' escape probability increasing with energy, or that the higher energy particles spend more time in lower density regions. In either case, the energy dependence must be incorporated into the galactic transport model.

4. What we have learned and What we must still learn

The relative abundances of elements in the cosmic ray source(s) are unlike the composition of our Solar System, which is the benchmark to which we compare. Solar system composition [21, 22] represents the material in the galaxy about 4.5 billion years ago when our solar system started to form. The cosmic rays, however, are much younger, about 20 million years. The differences between the cosmic ray source and the solar system do not correlate with any particular process of nucleosynthesis or known galactic chemical evolution. However, it was noticed many years ago that there is a correlation with the First Ionization Potential (FIP) of the elements. Plotting the ratio of the cosmic ray source (CRS) to the solar system (SS), both normalized to the same element (usually Si or H), produces a plot such as is illustrated in figure 3. The elements with low FIP seem to be in agreement with a solar system source, while high FIP elements are depleted in the cosmic ray beam by nearly an order of magnitude. If treated as an ionization equilibrium situation such a pattern implies temperatures of about 10,000 degrees K, similar to the temperatures of stellar photospheres. This led to many models in which the cosmic rays originated from stellar atmospheres or stellar flares, but a suitable acceleration mechanism was lacking.

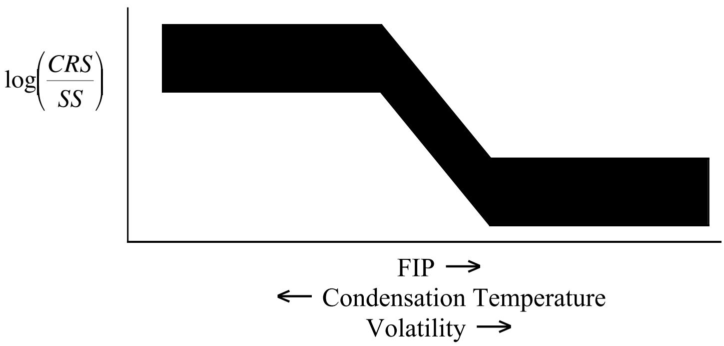

Fig. 3. Schematic representation of the First Ionization Potential dependence of the cosmic ray source to solar system relative abundance ratio. Other parameters that correlate with FIP are indicated.

First ionization potential is but one atomic property that can describe this situation. An element's condensation temperature correlates well (inversely) with FIP as does an element's volatility, and these are indicated in figure 3. The low FIP elements have the highest condensation temperature and are known as refractory elements. The noble gases which display the highest FIP are also the most volatile elements. One should also note the correlation between the abundance depletions in the gaseous phase of the ISM and the volatility, with the depleted elements bound into interstellar grains. The clear implication of these other correlations is that matter to become cosmic rays is not necessarily in the gaseous phase but may be in dust grains [23, 24].

The FIP versus volatility correlation is not perfect. There are several elements which defy the correlation, and these are the keys to deciding between the different interpretations. Of the set Ge, Rb, Sn, Cs, Pb and Bi, only Ge, Sn and Pb have a measured abundance, and the implication is that FIP is <u>not</u> the controlling factor [25]. However the current measurements need confirmation, and this is one of the reasons that improving the resolution, and statistics, in the UH charge region was cited above as one of the challenges for the coming decades.

Another source of information is provided by isotopic composition which is not subject to atomic fractionation. With the ACE data, there are now isotopic abundances for all of the major elements up through Nickel. For these we do the same thing, *i.e.* use the propagation model to determine the isotopic ratios at the cosmic ray source. Considering 18 isotopes, from ^{24}Mg to ^{62}Ni, with large primary components, the source ratios are found to be consistent with solar system values to within 20% [26] (uncertainties come both from the nuclear cross section values used in the calculation and from the measurements.) This remarkable result suggests that, at least for the refractory elements, the cosmic ray source material is essentially identical to solar system material. Since the elements and isotopes in this range are known to arise from a variety of sources, Type Ia and Type II supernovae as well as intermediate mass stars that undergo mass loss, it is unlikely that the cosmic ray source accelerates freshly synthesized matter.

Another constraint is obtained from the electron capture isotope ^{59}Ni which is synthesized in supernova explosions and subsequently decays to ^{59}Co with a half-life of 7.6×10^5 years. If ^{59}Ni is accelerated to cosmic ray energies, it will be fully stripped and electron capture decay will be forbidden. The ACE measurements show essentially no surviving ^{59}Ni, and an upper limit was reported. This implies that there must be a time delay of at least 100,000 years between the nucleosynthesis event and the acceleration of cosmic ray source matter to high energy [27].

Another issue is the question of re-acceleration during propagation. While wandering through the galaxy, cosmic rays can encounter supernova shocks or are scattered by moving magnetic turbulence. In such encounters, the particles may gain energy via first or second order Fermi processes. Such energy gains, if significant, would alter the amount of material traversed or change the decay of radioactive species due to altered time dilation. Propagation models including re-acceleration have been developed and can reproduce the secondary to primary ratios. However, there are electron capture isotopes that are produced primarily as secondaries, *e.g.* ^{44}Ti, ^{49}V, ^{51}Cr produced mainly from fragmentation of iron peak elements. If produced at high energy, the isotope will be fully stripped and will not decay. At lower energies, circa 100–200 MeV/nucleon, electron attachment becomes probable and the isotopes will decay. If re-acceleration is significant, it will move these isotopes from energies where decay is possible to higher energy where there is no decay and thereby alter the energy dependence of the ratio *e.g.* ^{49}V/^{49}Ti. ACE has been able to measure these isotopes at energies below 500 MeV/nucleon and has shown that the energy dependence of the ratios is in agreement with expectations for electron capture decay [11]. When models with re-acceleration are employed, the results are mixed. Some ratios prefer to have re-acceleration while others do not. This may indicate an effect of the fragmentation cross sections which are not all measured as accurately as necessary. In any case, the resolution of the re-acceleration question using electron capture isotopes awaits additional data and analysis.

The preceding discussion has been largely in terms of the refractory elements and does not apply, necessarily, to the more volatile elements. In particular, the one confirmed isotopic anomaly in the cosmic ray source, the ^{22}Ne/^{20}Ne ratio, remains with an overabundance of a factor of three to five in the cosmic ray source compared to the solar system. Whether this is due to special circumstances contributing to the cosmic rays or represents an underabundance in the solar system relative to other parts of the galaxy remains unresolved.

Moving to higher energy, the smoothness of the cosmic ray energy spectrum suggests that it is the same process which accelerates particles from low energy to the HE and VHE regimes. This implies that the cosmic ray source material is the same for all energies. An analysis of the source relative abundances, then, should show the same dependence on FIP or volatility as was sketched in figure 3. If that should not be the case, it would imply a different source for the high and low energy cosmic rays. To the limited extent that current data has allowed such an analysis, the high energy results are consistent with figure 3. Extending such an analysis through the HE and into the VHE region is of paramount importance.

It should be easier to determine the source composition at higher energy, since the number of secondary nuclei is decreasing, as the amount of material traversed decreases. However, to perform the unfolding accurately, we need to determine the correct amount of material traversed by extending the secondary to primary measurements, B/C for example, to higher energy. Does the ratio continue to decrease with energy or does it reach a limiting value, as some models predict (*cf.* curves in figure 2)? The importance of this question for understanding the origin and propagation of the cosmic rays has been re-emphasized recently [28], including predictions from a variety of models. However, for balloon experiments, there is always a layer of atmosphere above the experiment that acts as a 'source' for secondary production. Counteracting this background and measuring a very small B/C ratio is indeed a challenging problem for the next generation experiments.

Moving to the top left of Table I, both positrons and anti-protons have now been measured into the HE region. Positrons and anti-protons are secondary species produced by interactions in the ISM. In contrast, their oppositely charged partners, electrons and protons, both have primary components produced in the cosmic ray source(s). Positrons have been measured up to ~ 50 GeV while anti-proton measurements extend to a similar energy. Overall, the results are consistent with the secondary production models.

Positron and anti-proton measurements are particularly important since these two species are final states in the decay of many candidate dark matter particles [29]. In the positron to electron ratio, a small excess is observed in the 7–10 GeV range, which might be the product of neutralino decay

[30]. Similarly, a small excess of anti-protons around 200–300 MeV has been interpreted in a similar way. In both cases, the excess must be measured relative to the expected secondary component, whose calculation is itself subject to some uncertainty. In the case of low energy anti-protons, the effects of atmospheric secondaries and of solar modulation must also be taken into account. While there are 'hints' of possible dark matter signatures, more detailed experiments will be necessary before any dark matter connection is established.

The magnetic spectrometers that have been flown can also separate nuclei and anti-nuclei, and searches for anti-helium have been made. The limit on the presence of anti-helium has decreased steadily with time to a current value just under 10^{-6}. The AMS experiment to fly on the International Space Station in the next few years may be able to push that limit down by another three orders of magnitude.

5. The 'Standard' Model

The cosmic rays interact with interstellar matter and leak out of the confinement region. To maintain the cosmic ray pressure in the galaxy, these particles must be continuously replenished. This requires an energy input into cosmic rays of 10^{40}–10^{41} ergs/second. This rather large power requirement led naturally to a presumed connection with supernovae [31] which provide an average power of $\sim 10^{42}$ ergs/sec. With a conversion of 1–10% of the supernova power into relativistic particles, the cosmic rays can be maintained. Note that it is the supernova energy that is needed, not necessarily the material ejected in the explosion.

The connection is supplied by the acceleration mechanism. With the discovery that diffusive shock acceleration, basically a first order Fermi process [32], operates efficiently at the discontinuity where the outward moving blast wave from the supernova explosion interacts with the surrounding medium, the model was complete. Downstream and upstream of the shock, the magnetic fields confine the particles, forcing many crossings of the shock boundary, with the charged particle receiving an acceleration upon each crossing *e.g.* [33]. The acceleration theory has been well developed and has been tested with direct observations of particles accelerated at shocks within our Heliosphere. The theory predicts power-law spectra with the same power law index (in magnetic rigidity) for all nuclear species. The expected index is in the range 2.0–2.2. In addition, there is a maximum energy for the accelerated particles due to the finite lifetime and maximum size of a supernova remnant (SNR). For a model supernova remnant and an assumed magnetic field of 3 μG, this maximum energy is $Z \times 10^{14}$ eV where Z is the charge of the nucleus [34], but this maximum energy depends upon the actual conditions.

Unfortunately, supernovae and their remnants are not so 'standard'. Types Ia and II supernovae results from different stellar evolution. Massive star explosions often occur in large OB associations whose previous supernovae may have swept out a large cavity (bubble or super-bubble) leaving behind some of their ejecta. The shock wave expands into a medium which can vary from normal ISM, for an isolated supernova, to shells produced by earlier mass loss events, to a rarified medium within a super-bubble. The interior of SNRs is observed to be very turbulent and the shells often break into sub-sections showing 'hot spots'. Expansions can also be non-spherical depending upon the environment. Then, there is the magnetic field needed to confine the particles in the vicinity of the shock. The field strength can vary considerably, as can the mach number of a shock. Theory shows that such variations lead to a different spectrum for the accelerated particles.

Maintaining the galactic cosmic rays requires a superposition of many such events, and it is somewhat surprising that "features" from different events are not observed, rather are absorbed into the overall sum. The many possibilities provided by SNR acceleration have led to a torrent of papers and different models, as well as to a deeper exploration of the process, including important non-linear effects. An intriguing suggestion is that, while superposition of many events is required over galactic time scales, what we observe today may be a cosmic ray beam dominated by a single, relatively recent, nearby supernova [35, 36]. This removes any effect of superposing many events, and can explain the observed energy spectrum. It may also explain the solar system like composition observed for the cosmic ray source material. The postulated nearby source is the Monogem Ring, the result of a supernova explosion about 100,000 years ago [37].

6. The high energy challenge

The VHE and UHE regions contain the only known changes in the cosmic ray energy spectrum, the "knee" at a few times 10^{15} eV and the "ankle" at a few times 10^{18} eV. The knee represents a steepening in the spectrum by ~ 0.5 in the power-law index. The 'ankle' is the region in which the spectrum flattens again to approximately the pre-knee spectral index. It is at the energy of the ankle that the proton gyro-radius is about the size of the galactic disk, so that at energies beyond the ankle the particles may not be bound to the galaxy. Thus, in the UHE region, the cosmic rays may well be extra-galactic in origin. Since there are several other papers dealing with the physics and astrophysics of UHE particles, they will not be discussed further in this summary.

Returning to the VHE region, it can be subdivided into the energy region approaching the knee, and the region transitioning the knee. In the former region direct, particle-by-particle measurements are possible, while information from the knee and above is largely derived from air shower measurements. A major goal for the future is to obtain appreciable overlap in energy between the two techniques, to enable inter-comparison of results.

The available direct measurements are mainly from emulsion chamber experiments and have been discussed elsewhere [38]. The main result is a difference in the spectral indices of different elements or groups of elements. Helium, for example, shows a smaller power law index than H, with the effect at the two sigma level. Such a difference has been reported at HE as well [39]. Further, the CNO, Ne-S, and $Z \geq 18$ ("Fe") groups all show slightly different spectra with CNO and "Fe" having the flattest spectra.

The airshower data at VHE is not completely consistent from one experiment to the next, but the consensus seems to be that the average composition becomes heavier as the knee is crossed. That would be consistent with element spectra whose spectral indices are smaller than the proton index, since the heavy nuclei would become a larger and larger fraction of the cosmic rays as the energy increases. While spectral differences that have been reported may explain the changing average composition, they are difficult to understand within the SNR acceleration picture.

What then can explain the knee? The steepening of the spectrum at the knee signifies a deficit of particles, with the difference (relative to the pre-knee spectrum) increasing with energy. This absence of particles has been, over the years, attributed to many things: *(i)* increased loss from the galaxy, *(ii)* new interaction channels, *(iii)* termination of the cosmic ray 'accelerator'. Currently, the latter is favored since the SNR acceleration mechanism is expected to have a maximum energy in the range of the knee. In fact, if the currently measured spectra are extrapolated upward in energy and a SNR acceleration cut-off of $Z \times 10^{15}$ eV is assumed, the summed "all particle" data is in reasonable agreement with the all-particle spectrum measured by the air shower experiments. What happens is the protons drop out at 10^{15} eV ($=$ PeV), Helium continues to 2 PeV and terminates, carbon extends to 6 PeV, *etc.*, with Iron ending at 26 PeV. (Of course, if we include UH cosmic rays, they would continue to higher energies.) This is "suggestive" but is far from being a viable model. For example, what accounts for the particles at still higher energy where there are indications that the composition is again dominated by a light component? Clearly, there is much work to be done, and the newer balloon experiments such as ATIC, TRACER and CREAM, see [38], are designed to provide the needed experimental data.

Another source of information is provided by high energy electrons. Electrons are unique in that they lose energy by synchrotron and inverse compton processes and the energy loss rate increases with energy. Thus, the electron spectrum steepens rapidly in the VHE region. Moreover, the VHE electrons cannot travel very far from the sources before their energy is expended. Studying electrons at VHE provides a means to look at nearby SNR. It should be noted that the presence of high energy electrons in SNR has been confirmed through measurements of the synchrotron radiation the electrons produce.

Figure 4 shows existing data on the cosmic ray electron spectrum (multiplied by E^3) in the HE and VHE region. The solid curve shows the propagated galactic spectrum taking into account the loss processes, and this spectrum effectively terminates at a few TeV. Predicted additions from Vela and Monogem, nearby recent supernovae, are indicated. (Three distances to Vela are shown for comparison.) The experimental challenge is clear. Sufficient exposure, with good proton rejection, must be obtained to investigate possible electrons from these nearby sources. If they can be found, it would be a striking confirmation of the SNR acceleration model.

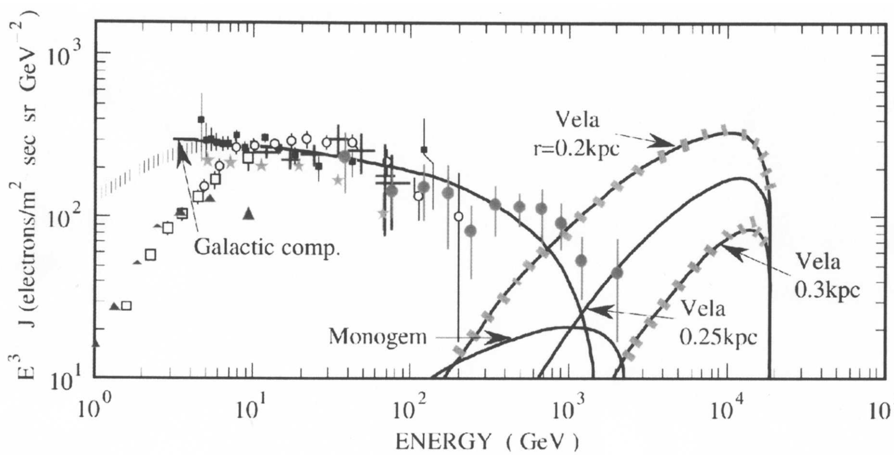

Fig. 4. Compiled cosmic ray electron data and predictions for two nearby sources (adapted from [40]).

7. Conclusions

The galactic cosmic rays are a profound source of astrophysical information about our galaxy, and explosive events within it. The composition of the cosmic ray beam suggest a source composition very similar to the matter in our solar system and argues against the acceleration of freshly synthesized material. The energy spectra and the composition at VHE provide the information needed to understand the SNR acceleration process and, ultimately, the origin of the knee. The astrophysical interpretation has improved tremendously in the past decade, but there remain many fascinating questions for future work.

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