On the Origin of Cosmic Rays

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Abstract

The problem in identifying the sites of origin of Galactic Cosmic Rays (CRs) is reviewed. Recent observational evidence from very-high energy (VHE, energies above 100 GeV) \( \gamma \)-ray measurements is in contradiction with the surmise that synchrotron radiation from relativistic electrons is indicative for hadron acceleration. It rather points to a CR-acceleration efficiency of supernova remnants (SNRs)\(^1\) below one percent, much less than the value required if these objects were to be the main sources of Galactic cosmic rays (about 30\%). Observations of CR anisotropy and the emission of low-energy (energy < 10 GeV) \( \gamma \)-rays from the Galactic disk indicate that the sources of low-energy cosmic rays are distributed with a Galactocentric radial scale length in the order of 25 ± 10 kpc, much larger than expected if SNRs are the main sources of CRs. These two facts - together with the body of evidence from CR isotope abundances - strongly suggest that a new class of astrophysical objects - distinct from SNRs and located mainly in the outer reaches of our Galaxy - is the major source of hadronic CRs in our Galaxy.

The basic observational features of ultra high-energy (UHE, energy > 10\(^{19} \) eV) CRs are most naturally understood if the same CR sources accelerate CRs up to the highest observed CR energies. Proposals for the nature of a new source class are mentioned. The origin of CRs is still as much shrouded in mystery as it was in 1957, when Philip Morrison wrote a seminal review about CR origin. The potential for discoveries is thus great.

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\(^1\) The term “SNR” is below always used in the sense: “the well known non-relativistic ejecta of supernova with a typical kinetic energy of 10\(^{51} \) ergs”
Thus in the 40 plus years since the publication of Morrison’s seminal paper[74] ... we have come no closer to a definitive model of cosmic-rays origin.

Trevor Weeke, August 1999[112].

Until recently the hypothesis that cosmic rays originate in the flashes of supernovae has been based solely on energy considerations - evidence that is still far from adequate.

Vitaly Ginzburg, July 1953[52].

1 Introduction

1.1 The problem in historical perspective - outline

Around 1930 Millikan, Cameron[73] and Regener[88] realized that the energy density of cosmic rays in space is about as high as that of integrated star-light. This made clear that cosmic rays are an important cosmic phenomenon, and two questions were raised.

1. By which mechanism are cosmic rays accelerated?
2. Where and in which sources does this occur?

In this manuscript I try to summarize what is presently known about the answer to the second question. I strive for brevity and will review neither the theoretical nor the experimental literature exhaustively. My style is inspired by a memorable article of Philip Morrison with almost the same title in 1957[76] (“On the Origins of Cosmic Rays”), because our situation concerning the second question is hardly better than the one described by Morrison like this: “the broad road (towards the answer) is finally visible, but the details may well be all wrong[76]”.

Up to 1948 both questions remained a complete riddle, revealing a deep fundamental lack of knowledge of the physical world. Highly speculative origin theories - without a firm basis in contemporary physics - were proposed. Millikan[74] suggested a new fundamental production process and Lemaitre[66] explained cosmic rays as relics of the early universe. These ideas stood at the cradle of modern nuclear astrophysics and cosmology but did not really advance cosmic-ray physics. Two publications by Baade and Zwicky from 1934[8], suggesting an origin of CRs in extragalactical supernovae, stand out for their impressing far-sight[8].

Then, in a brief, productive “golden period” - from about 1948 to 1962 - Fermi conceived the fundamental theoretical concept for the acceleration mechanism and several crucial experimental discoveries provided the basic framework in which we still grapple today for an answer to the question of the site of origin. Fermi’s brilliantly simple idea was the realization that nuclei colliding via magnetic interactions with macroscopic gas clouds reach

2Their basic idea was that relativistic particles with a total energy between $10^{53}$ and $10^{54}$ ergs would be ejected in a supernova. These particles indirectly “heat” the stellar debris and thus lead to the visible SN event. It might still turn out that this image is very close to being correct.
equilibrium only when their energies are similar, i.e. when the nuclei possess macroscopic kinetic energies. Henceforth the question was no longer “how can such high energies be reached?” but “under which circumstances and with what time scale?” This was the death-blow for the early speculative theories, CR origin had become a problem of conventional astrophysics. Since the mid 1980s very speculative theories are considered once again, see section 4.2.

The most important experimental achievement of the “golden period” was arguably the determination of the CR spectrum as a function of total particle energy. Today the flux of the dominating hadronic component, consisting of protons and heavier nuclei, of the local non-solar cosmic rays (CRs), is determined at energies between about 0.1 GeV and \(3 \cdot 10^{20}\) eV. Neglecting solar modulation effects, the all-particle CR flux can be described by power-laws with indices in the narrow range between -2.5 and -3.2 over the whole range (more than 10 decades) in energy (see data points in fig. 1) and a single power law with an index of -3 is quite a good approximation to the experimental data (see thin dashed line in fig. 1).

A framework for the explanation of this spectrum, assuming various different sites of origin, is at present practically universally accepted and is sketched in fig. 1. In sections 2 and 3 I will critically discuss the origin of the low-energy and very-high energy component, respectively. Following a seminal paper by Biermann and Davis section 4 explains why observations make necessary a departure from the conventional framework. Section 5 briefly discusses two recent and one historic proposed alternative major source of CRs. In the final section 6 I will give a personal interpretation of the current situation and lay down some questions to be answered by future research.

1.2 Cosmic-Ray Origin: the single most important problem of “Astroparticle Physics”

When I talk to younger colleagues in the field of astroparticle physics I get sometimes the impression that for them, the question of low-energy cosmic-ray origin is some old problem left over from the last century. Nothing could be further from the truth. Cosmic-ray origin is the only important physics problem where astroparticle physics is called upon to take the lead - both theoretically and experimentally - in providing a full solution for all energies. In other areas, like the physics of active-galactic nuclei, the emission-mechanism of pulsars, the quest for dark matter or the nature of cosmological background fields astroparticle physics just supplies some pieces to jigsaw puzzles being assembled by others.

2 Origin of “low-energy” (energies below the “knee”) CRs
2.1 The proposal of SNRs as sources of the low-energy component

In 1953 Iosif Shklovsky\textsuperscript{3} - armed with his recent identification of the bright radio source Cas A as the remnant of a historic supernova explosion (SNR)\textsuperscript{4} - proposed that SNRs (rather than SNe themselves) are the main sources of Galactic cosmic rays\textsuperscript{5}. Shklovsky gave two arguments for his idea:

1. the total power of the of CRs injected into the Galaxy is “similar” to the kinetic explosion power of a Galactic supernovae (i.e. $10^{51}$ erg/50 years)\textsuperscript{6}. Quantitatively the power of the injected CRs was determined to be about 30 % (with an uncertainty of a factor 3)\textsuperscript{7} of the total kinetic power of young Galactic SNRs\textsuperscript{8}.

2. SNRs are most prominent non-thermal radio sources because they produce non-thermal electrons copiously. Shklovsky wrote\textsuperscript{9}: “…it is quite natural to consider that simultaneously with relativistic electrons, also occur relativistic heavy particles.”

2.2 A guiding principle: is synchrotron emission indicative of the total non-thermal acceleration power?

Shklovsky’s second point fell on fertile ground. In the year before Ludwig Biermann had made the \textit{“tentative assumption that the radio emission indicates the order of magnitude of all non thermal emissions.”}\textsuperscript{10}. Henceforth, the assumption that the main CR sources are prominent radio sources was a beacon to most theoretical studies on CR origin. In 1962 Geoffrey Burbidge formulated the idea that the other class of celestial radio sources that rival SNRs in apparent luminosity, active galaxies (typified by Cyg A, the second brightest radio source in the sky after Cas A) are the main sources of all cosmic rays\textsuperscript{11}. The following decade’s discussion concentrated on a heated controversy between Burbidge and Vitaly Ginzburg, who had become the main proponent of Shklovsky’s idea\textsuperscript{12, 13}. A discussion of alternatives (such as e.g. a stellar origin of a very-low energy component as favored by Morrison\textsuperscript{14} or the ideas of Biermann and Davis\textsuperscript{15}, discussed in section 3) fell completely by the wayside.

\textsuperscript{3}An identification that was initially vehemently resisted by Walter Baade\textsuperscript{16} who had proposed SNe as cosmic-ray sources some 20 years earlier.

\textsuperscript{4} Shklovsky’s priority on this crucial idea is clearly stated by V.Ginzburg in an early review\textsuperscript{17}.

\textsuperscript{5} This “equality” does not point directly to SNRs as the site of CR acceleration, rather it only points towards a possible connection “CRs - supernovae”.

\textsuperscript{6}This is the most recent value (a previous careful determination gave the range of 10 - 30 \%\textsuperscript{18}). In Shklovsky’s article the total injected power by SNRs was estimated to be about 2 orders of magnitude smaller (this was sufficient given the incomplete knowledge of Galactic CR propagation in 1953). Such a smaller efficiency is in line with the expectation of Biermann and Davis (see section \textsuperscript{5}).

\textsuperscript{7}Such an argument was first made by Baade and Zwicky\textsuperscript{19} in an extragalactic context. With the same values and assumptions about propagation and explosion energy as Shklovsky, it was first made by ter Haar\textsuperscript{20}. 
2.3 The present situation: are SNRs the main source of low energy CRs?

In spite of enormous advances in experimental techniques in the half century that has elapsed since the publication of Shklovsky’s paper, **not a single additional observational fact directly supporting the hypothesis that SNRs are the major source of Galactic cosmic rays has come to light.**

To make matters worse - in what I consider to be the most important experimental discovery in CR physics since the 1950s - it was recently learnt that Cas A is **not** an important source of hadronic cosmic rays (see section 3.1 for further discussion). This saps the foundations of Shklovsky’s second argument. The beacon mentioned in the previous subsection - that still guides many - threatens to have misled us for nearly half a century. **The dominant sources of hadronic CR are either SNRs or they are not prominent radio sources.** The sole direct evidence in favor of a SNR origin of CRs is again the ter Haar’s energy argument, *evidence that is still far from adequate*\(^8\)

*But if not SNRs, then what?* Let us take a big step back in time and reconsider some early arguments **against** SNRs as CR sources in the light of today’s body of experimental evidence, in an attempt to point a way out of this impasse.

3 A Path not taken - 1958: Returning to a critique by Biermann and Davis

Near the end of the “golden period”, in 1958, two of its principal architects, Ludwig Biermann and Leverett Davis, summarized some lessons learnt\(^9\). Their analysis, though certainly noticed\(^10\), had little impact on the consecutive research. This is a pity since their doubts and some of their surmises have been born out by observations in a truly impressive way.

3.1 Acceleration efficiency in SNRs

Biermann and Davis write: “**With the present frequency of supernovae, it would just be possible to account for the acceleration of cosmic rays if one assumes a very high efficiency for the conversion of kinetic to cosmic ray energy. Even with a higher frequency in the early stages [of Galactic evolution], the efficiency remains so high (several percent) that the present authors find this proposal difficult to accept.”**

Today’s value for the required efficiency at about 30 %\(^11\) is even higher. Biermann and Davis refrain from telling us why to them an efficiency of several % seemed unrealistically

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\(^8\) The gist of a prominent colleague’s only reaction to a recent manuscript was : “Nobody believes that because the proposed CR-producing ejecta were not seen in the radio.”

\(^9\) Their collaboration on Galactic CRs was explicitly mentioned in the laudation on occasion of the award of the Bruce medal to Biermann.

\(^10\) The paper was quoted only five times, the last time in 1969.
high, but it is easy to guess the reason for this judgment. As pioneers of solar-system CR physics, they knew that the efficiency of hadron acceleration to relativistic energies in large solar flare events is typically 0.1 %\textsuperscript{11}. The velocities, matter densities and magnetic field strengths involved in these events are not radically different to those in SN ejecta. However, there are also important differences in temporal and spatial scale\textsuperscript{12}, so Biermann and David prudently did not cite solar-system evidence in support of their doubt. Today’s direct evidence on the hadron acceleration efficiency in SNRs strongly supports their doubts.

Accelerated hadrons interact with ambient matter producing $\pi_0$ mesons. The level of very-high energy $\gamma$-ray radiation expected from $\pi_0$ decay allows to derive the efficiency of proton acceleration\textsuperscript{42} and has been searched for in a considerable number of SNRs using air-shower arrays and air Cherenkov telescopes. Let’s take a closer look at the two most interesting cases.

### 3.1.1 SNR G78.2+2.1 - a cosmic beam dump

G78.2+2.1 - probably the remnant of a core-collapse supernova in the Cyg OB9 association $1.4 \pm 0.6 \times 10^4$ years ago - is fourth brightest SNR at 1 GHz in the sky\textsuperscript{33}. At a distance of only $1.5 \pm 0.3$ kpc it subtends an angle of 1 degree, about twice as much as the moon. Based on various observational indications Pollock\textsuperscript{83} suggested that a bright “hot spot” (called “DR4”) of radio synchrotron emission in the south-east corner of the SNRs radio shell is due to the dense molecular cloud Cong 8\textsuperscript{33}, that was recently hit by the advancing SN shock front. Since the time Pollock wrote the paper, Fukui and Tatematsu\textsuperscript{50} have reconfirmed a CO emission at 2.6 mm and Wendker et al.\textsuperscript{114} found H$_2$CO absorption in four out of five positions in DR4. Because CO and especially H$_2$CO are indicators of high density, “...there is good evidence that interaction with quite a dense cloud is occurring in this part of the SNR. (cited from \textsuperscript{114})”. The reality of the association between shock wave and molecular cloud has been doubted because Frail et al.\textsuperscript{49} failed to find OH(1720) MHz Maser emission from SNR G78+2.1. This is unwarranted, Frail et al.\textsuperscript{49} write:”Since masers are a nonlinear physical phenomenon, depending sensitively on input parameters the non detection of OH (1720 MHz) maser emission does not in itself rule out an interaction.”

In fig.\textsuperscript{3} I compare the detailed shape of the IR emitting region at 100 $\mu$m as measured by the IRAS satellite (taken from IRAS ISSA server\textsuperscript{61}) and DR4 at 92 cm as measured by the Westerbork radio telescope (from the WENSS survey\textsuperscript{115}). The position and general elliptical shape, with a major axis from SW to NE, of the IR and radio emitting region

\textsuperscript{11} The stress is on relativistic, the efficiency for acceleration to lower, but still non-thermal energies can be much higher.\textsuperscript{4}

\textsuperscript{12} The acceleration efficiency for relativistic electrons in nova explosions - intermediate in energy between solar flares and supernova outbursts - has been been determined to about 1 %\textsuperscript{44}. This value is similar to the one in SNRs (section 3.3). Perhaps an efficiency for acceleration to relativistic energies in the order of 0.1 - 1 % is typical for non-relativistic shocks in a magnetized low-density medium for all species.
are similar. This morphological resemblance suggests that indeed a molecular cloud was heated and compressed by the SNR shock wave.

G78.2+2.1 accelerates electrons to a spectrum with a power-law index of \(-2.08 \pm 0.04\), very close to the theoretically preferred value of \(-2.1\). This makes G78.2+2.1 an excellent candidate for a typical hadronic CR accelerator. The spectral index within DR4 is similar to the one in the rest of the remnant. The entire cloud must then act as a “beam dump” for accelerated protons. The high matter density in the molecular cloud and relative closeness of the remnant make DR4 a most sensitive test-bed of hadron acceleration in SNRs.

Fig. 4 compares various observational upper limits on VHE emission from DR4 with theoretical expectation, calculated under the assumption that 10% of the kinetic explosion energy was converted to hadronic CRs. The most restrictive limit (from 47 hours of on-source measurement with the HEGRA system of telescopes) falls below the expected value by more than a factor of 100.

### 3.1.2 Cas A - cradle and bier of the belief that SNRs are the main source of CRs

Cas A, at a distance of 2.8 - 3.5 kpc, is the remnant of Flamsteed’s type Ib supernova “3 Cas” in the year 1680. It is the brightest non-thermal radio source in the sky and one of the best studied and understood non-thermal objects. It was Cas A that inspired Shklovsky to propose that Galactic CRs are mainly accelerated in SNRs. His idea was refined in the 1970s by models in which the CRs are mainly accelerated at the outer plane shock front via the first-order Fermi mechanism. Recently very clear experimental evidence from X-ray measurements for such a shock was found in Cas A (see fig. 2).

Berezhko, Pühlhofer and Völk carefully calculated the expected VHE \(\gamma\) flux from Cas A, under the assumption that CR acceleration efficiency of Cas A is 20%. They point out that the observed flux of \(\gamma\)-rays with energies above 500 GeV falls below the expected flux by more than a factor of 100. The observed signal might well be due to inverse Compton emission by CR electrons, that are known to exist in Cas A. The discrepancy would then increase.

### 3.1.3 SNRs are not the main sources of cosmic rays - their efficiency for acceleration is too low

The upper limits on \(\gamma\) radiation from these two remnants bound the hadronic acceleration efficiency to about \(20/100=0.2\%\). This shows that the intuition of Biermann/Davis was correct: the efficiency with which the kinetic energy of SNRs is converted to CRs is not much larger than 1%, thus excluding SNRs as the major source of hadronic Galactic cosmic rays.

Let us consider various attempts to avoid this conclusion.
The different ages of Cas A and G78.2+2.1 exclude that the small VHE $\gamma$-ray flux is due to a long time scale of hadron acceleration ("late injection") or faster than usually expected diffusive CR loss from the remnant.

There is a handful of other SNRs for which less restrictive or more model-dependent upper limits from Cherenkov telescopes\cite{108,22,92} and low energy-threshold air-shower arrays\cite{75,84} below the theoretical predictions exist. Therefore speculating that only a small fraction of "special" SNRs are the main sources of CRs quickly runs afoul with the required efficiency of particle acceleration that can hardly be much higher than the 30% required if all Galactic SNRs contribute equally\cite{13}.

The non-detection of $\gamma$-rays in the required amount might indeed be due to an upper energy cutoff below the threshold of the detectors (at 200 GeV and higher for various Cherenkov telescopes and at 3 TeV and higher for various arrays). Berezhko and Völk\cite{14} considered this possibility and aptly concluded: "\textit{Note however, that in this case SNRs would hardly be considered as the sources of Galactic CRs.}\cite{14}"

Finally, the enormity of the discrepancy for the two cases presented above precludes to invoke a SNR source spectrum steeper than the one expected from the standard theory (power-law index of -2.1). The steepest index compatible (with difficulty\cite{70}) with observational evidence from CR abundance ratios is -2.4. This value still results in a discrepancy from observation by a factor 10.

### 3.2 Anisotropy and Galactic distribution of CRs

Biermann and Davis also directed their attention to air-shower experiments that had just shown that the amplitude of anisotropy of Galactic cosmic rays was surprisingly small, below $10^{-3}$ up to $10^{14}$ eV and still below 10% at $10^{17}$ eV. These experimental results have stood the test of time\cite{35,94,31,56}.

If cosmic rays are produced mainly within the solar circle (as is the case if SNRs are their dominant sources) at earth their diffusive leakage out of the Galaxy is equivalent to a slow net motion towards the Galactic anti center. A finite anisotropy is then expected due to the so called "Compton-Getting" effect\cite{32}: less particles are incident in the direction of net motion. The most recent detailed analysis of this effect\cite{86} finds that the amount of anisotropy expected at an energy of $10^{14}$ eV is far larger than observed in three out of four considered models (by factors between 5 and 40). The remaining model manages to reproduce an anisotropy of $10^{-3}$ - but only at the price of implausible ad hoc assumptions, like a CR source spectrum of the form $\sim R^{-2.4}/(1+(2/R)^2)^{1/2}$ (unexpected in any theory) - here R is the rigidity in GV - and an energy dependence of a cosmic-ray diffusion constant in flat contradiction to the most recent analyses of CR abundance ratios\cite{70}.

\textsuperscript{13} This is only true of the CR producing SNRs are already known. The idea of an hitherto unknown class of "SNRs" with very different properties is indeed plausible and the subject of some proposals presented in section 5.

\textsuperscript{14} Because the unity of the spectrum up to the knee implies a common origin of all CRs below the knee.
This problem is sometimes dismissed as mere coincidence. Perhaps the effects of various local sources of CRs conspire to result in an unusually small anisotropy near earth? Such a “conspiracy” appears unlikely when considering the determination of the CR density within the Galaxy by using observations from the 1970s onwards of low-energy $\gamma$-rays. The small anisotropy turned out to be the first indication of a deep lying problem.

The radial scale length of the cosmic-ray density - derived in the interval between 5 and 20 kpc - has a value between 16 kpc and 34 kpc in various recent determinations based in data obtained with the EGRET experiment\[99, 46, 60\] (earlier determinations based on SAS and COS-B data had given similar results). The space-density of SNRs is maximal at a distance about 4 kpc from the Galactic center and falls off with a scale length of about 5 kpc with increasing Galactocentric distance. Calculation of CR propagation based on this distribution predict a Galactocentric gradient which is about 3 - 5 times smaller than the observed one (see fig.5). The distribution of CRs within the Galaxy is much more homogeneous than expected, and this leads to the smaller than expected isotropy. There are two possible explanations for the discrepancy. Either the Galactic-propagation properties or the source location of CRs are different from what was thought plausible up to now.

With remarkable foresight Biermann and Davis had anticipated the problem just discussed from the limited data available to them and proposed an age of the observed cosmic rays of several billion years - one to two orders of magnitude larger than normally assumed. The longer diffusion time would indeed quantitatively result in the observed more homogeneous distribution of CRs in the Galaxy. However, their proposal was ruled out by later experimental results: In particular, the work on the relatively large concentration of unstable isotopes with lifetimes in the order of 10 million years (Be$^{10}$ and Al$^{26}$) - performed after 1958 - has convincingly proven that the CR ages cannot exceed several hundred million years. An alternative modification of the propagation properties suggests that the timescale of CR escape from the Galaxy might decrease towards the Galactic center\[21\]. This reduces the expected Galactocentric CR-density gradient. However the inferred total CR power of the Galaxy then exceeds the conventional value, thus requiring unreasonable acceleration efficiencies in SNRs (section 3.1).

It is then most natural to blame the Galactic location of the CR sources for the small Galactocentric CR-density gradient. The main cosmic-ray sources are distributed in the Galaxy with a Galactocentric scale length in the order of 25 ± 10 kpc. Various systematic uncertainties are still too large to derive the specific form of the source distribution - it might e.g. be exponential with a scale length of order 25 kpc or, alternatively, constant up to 25 kpc with an additional Galactic-center contribution of order of 10% of the total.

The distribution of SNRs in the Galaxy has not only be observed directly\[25\], but can also reliably be inferred - yielding similar results - from the one of their precursors, massive stars in our Galaxy and their brethren, pulsars\[46\]. This firmly excludes that SNRs may be distributed in the Galaxy as required by the assumption that they are the main sources
of CRs (as had been suggested by Strong and Moskalenko\cite{101}). There simply is no known class of potential CR accelerators located as required. Even Galactic dark matter (if it exists) is too strongly concentrated towards the Galactic center. **The main sources of hadronic cosmic rays must be a completely novel class astrophysical objects.**

### 3.3 The Origin of CR electrons in SNRs

Biermann and Davis continue after their rejection of the hypothesis of SNRs as the main CR sources:

> “Supernovae might well maintain the energy and number balance of the relativistic electrons responsible for the radio radiation of the halos. This is independent of the overall energy balance of the nuclei, which constitute $\geq 99\%$ of the cosmic rays.”

I think that Biermann and Davis were correct\footnote{See Dar et al.\cite{35} for a different view.}. In SNR 1006 about 1% of the remnant’s total kinetic energy was converted to relativistic electrons\footnote{This value was derived from the expressions in Ref.\cite{69} and the experimental flux at TeV energies\cite{103}.}. If this value is typical for Galactic SNRs, diffusive and radiative losses of Galactic CR electrons can be replenished by SNRs. Electrons are observed to be accelerated in SNRs up to the highest energies observed in the ambient electron spectrum\cite{103}. Moreover electrons - unlike the hadrons - are not found to have a homogeneous distribution in the Galaxy. Rather they are strongly concentrated towards the Galactic center. The radial scale length of the synchrotron emissivity of the Galactic thick disk is only $3.9 \pm 0.2$ kpc - in good agreement with theoretical expectation under the assumption of an origin of the CR electrons in SNRs\footnote{This conclusion only holds under the observationally plausible assumption that the mean Galactic interstellar B-field falls with a Galactocentric radial scale length much in excess 5 kpc.}. The excellent agreement between theoretical expectation and observational results under the assumption of a SNR origin of CR electrons makes the glaring failures of theory in the case of nucleons seem all the more alarming.

### 4 Origin of “high-energy” (energies above the “knee”) CRs

#### 4.1 Morrison’s dark question: absence of a cutoff in the CR spectrum near the knee

Philip Morrison\cite{76} already realized that SNRs cannot accelerate CRs to energies above about $10^{14}$ eV (the “knee” feature in the primary CR spectrum lies at a rather higher energy of $3 \times 10^{15}$ eV). His conclusion has since then been confirmed in numerous detailed theoretical studies\cite{62}. Impressive observational evidence on the reality of the cutoff\cite{114}
make it unlikely that recent ingenious suggestions (e.g. [12]) to circumvent Morrison’s limit are realized in SNRs. Morrison called the question of the origin of CRs with higher energies “dark”, a designation that remains completely appropriate to the present day [58].

4.2 Today’s second dark question: absence of the Greisen cutoff

The most recent results from the AGASA air shower experiment indicate that the CR spectrum continues with a differential index of about -2.5 from an “ankle” at $5 \times 10^{18}$ eV to $3 \times 10^{20}$ eV without any evidence for a spectral cutoff above $5 \times 10^{19}$ eV that is expected if UHE CRs are extragalactic [102]. The newest data [93] favor a power law from $5 \times 10^{18}$ eV to $3 \times 10^{20}$ eV without any structure. Three basic explanations have been brought forward to understand this [79, 20]:

1. Magnetic fields with a strength commonly encountered only in the center of large clusters unexpectedly exist also in extra-galactic space within about 10 Mpc of the Milky Way. This allows to “wash out” both anisotropies and the Greisen cutoff to a smooth increase of the spectral index in the mentioned energy range [96]. UHE CRs could then be due to active galaxies [87].

2. New physics occurs [97]. The ideas proposed have a similar status as the ones of Millikan and Lemaitre mentioned in the introduction.

3. UHE CRs have their origin in the Galactic halo [23, 59, 36].

I concluded in section 3.2 that the sources of low-energy CRs are a novel type of astrophysical object that is located mainly in the outer reaches of our Galaxy. The simplest point of departure for further research is then to adopt option 3 and to postulate that low and UHE CRs - and then indeed CR of all energies - have a common origin in the same novel source class. A “numerical coincidence” is in favor of such a paradigm. Magnetic confinement to our Galaxy is usually expected to set in at energies below a few times $10^{18}$ eV. The “ankle” is an increase in the spectral index of the primary CR spectrum by about 0.5 at about this energy. If only one source class dominates CR production at all energies, this coincidence can easily be naturally understood as the onset of Kraichnanian [28] Galactic confinement [105, 80].

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[19] Reynolds and Keohane conclude that in 14 SNRs they studied, only one (none) has a maximum electron energy above 100 (1000) TeV and that this limit should also apply to nuclei.

[20] I do not list the possibility of an origin in the Galactic disk that had been resurrected by some [44]. It requires an iron dominated composition above $10^{19}$ eV that was experimentally ruled out recently [2].

[21] In addition, a density ratio of CR producers inside and outside the local supergalaxy higher than the one suggested by independent astrophysical evidence has to be assumed [18]. It is obvious that this proposal was born of distress.
5 Alternatives to SNRs as CR major sources

To my knowledge there have been only two proposals about an origin of the bulk of cosmic rays proposing objects different from SNRs or pulsars\(^{22}\) within the last decade. In addition there is one historic proposal for an origin of CR in the Galactic halo.

5.1 Burbidge

In 1955 Geoffrey Burbidge\(^{23}\) proposed that CRs are accelerated up to the highest energy in the Galactic halo. Density irregularities with typical velocities of 200 km/sec were proposed as scattering centers. The ultimate energy source was imagined to be Galactic rotation tapped via turbulent hydromagnetic frictional effects.

5.2 Dar and Plaga

Gamma-Ray Bursts (GRBs) are non-thermal objects that are ill understood\(^{48}\). We are sure that sometimes GRBs occur in our own Galaxy, but where, how often and with what kind of remnants remains shrouded in mystery. It is then an obvious speculation to identify the main source of CRs with GRBs (section 5.2). This has been first proposed by Arnon Dar\(^{34}\) and worked out by Dar and Plaga\(^{36}\). In the latter paper GRBs are proposed as “universal” (dominating at all energies) CR sources. An origin of CRs in GRBs (at energies above the “knee”) was first proposed by Milgrom and Usov\(^{71}\), Vietri\(^{106, 107}\) and Waxman\(^{111}\). More recently Plaga\(^{82}\) proposed that bipolar supernovae\(^{109, 27}\) eject plasma clouds into the Galactic halo. These “plasmoids” are posited as the main sources of CRs. He based this scenario on the “cannonball model” of Dar and de R`u\(^{37, 38}\).

5.3 Dermer

It might be that Dar and Plaga\(^{36}\) fell into the same trap as Shklovsky\(^{95}\) and Burbidge\(^{24}\) before: again the source of CRs is directly identified with a bright non-thermal object in the sky. Charles Dermer recently suggested\(^{40}\) that - in addition to GRBs - a special type of stellar collapse event resulting in “fireball transients” (FT) occurs in the Galaxy. FTs are explosion events where \(\geq 50\%\) of the kinetic energy of the ejecta resides in relativistic \((\Gamma > 2)\) outflows. These outflows are proposed as the main source of Galactic CRs. GRBs would then only be the exceptionally baryon poor “tip of the iceberg” of the underlying novel FT source class, that is up to now mainly seen in the “light” of hadronic CRs. In Dermer’s scenario UHE CRs are produced on extragalactic GRBs, whereas Dar and Plaga propose Galactic GRBs also for this component.

\(^{22}\)The known population of Galactic pulsars falls short by about an order of magnitude in power to replenish the loss of Galactic CRs, even if high acceleration efficiencies are invoked.
5.4 General constraints on alternatives

I expect that the final answer will involve two ingredients: an origin mainly (but probably not exclusively) in the Galactic halo (taken from Burbidge and Dar/Plaga) and a process with a more direct and effective conversion of gravitational into kinetic energy than the one that shaped SNRs (taken from Dermer and Dar/Plaga). This leaves room for ideas quite different from the ones presented in this section, like an origin in a novel, primordial class of neutron or quark stars in the Galactic halo.

6 Conclusion - present status and future progress. A personal view

6.1 Present status - my view

Summarizing, SNRs are not the main sources of Galactic cosmic rays. SNRs are the main sources of one of its minor components, the electrons. The distribution of the actual main sources of Galactic cosmic rays differs from that of any other known class of potential CR accelerators. It stands to reason to speculate that these sources accelerate the complete CR spectrum up to the highest energies. The astroparticle physics community holds in its hands solid evidence for a completely novel type of astrophysical phenomenon. It must rise to the challenge to study this phenomenon, not by merely waiting for a serendipitous observational discovery but by systematic theoretical work on alternatives to a SNR origin of CRs.

6.2 Present status - prevailing view

The extremely disappointing experimental situation is not denied in the astroparticle/cosmic-ray community. It is generally and clearly stated that a CR origin mainly in SNRs is not certain. However, “faute de mieux” (“for lack of something better”, quote from a report by a working group on “tests of Galactic cosmic-ray source models”) any consideration of alternatives to SNRs as major CR sources is refused (not a single alternative to a SNR origin of the low-energy component is mentioned). Thus the prevailing view is that theoretical work on the origin of the low-energy component must remain restricted to the presently known class of SNRs, because it is “the (only) one model that has been worked out in some detail”.

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23 E.g. Matthew Baring skillfully avoids a personal endorsement in his summary of the 1999 26th ICRC (“... has led to the almost universal acclaim that SNRs are the site of CR acceleration. Yet ...”)
24 The strongly related concept of super bubbles - agglomerates of several old SNRs - as a possible site of CR origin is discussed, but the authors stop short of considering them as the primary CR source class.
25 formed of non-relativistic, very roughly spherical, SN ejecta
26 In support of my evaluation I quote from the rejection of an anonymous referee on a manuscript suggesting an alternative to a SNR origin of CRs. The referee had demanded an impossibly large
6.3 If the prevailing view continues to predominate...

...this will have two unhappy consequences:
1. The problem of the origin of CRs will probably be solved outside the astroparticle-physics community, when eventually other astrophysicists will stumble on the CR source class by chance.
2. The vital chance will be lost to be the first to study the new source class by means of CR evidence.

To illustrate the latter point, Arnon Dar and I proposed an extremely jetted geometry of GRBs (later worked out in detail by him and Alvaro de Rújula within the “cannonball model”) guided by CR evidence.

6.4 Future progress - some important open questions

Two questions are of primary importance for the problem of CR origin and serve as a possible point of departure for the research recommended in section 6.1. The third one is of more general interest.

1. There is solid observational evidence that some fraction of supernovae involves the ejection of ultrarelativistic plasma with a total kinetic energy larger than the one of SNRs (the most recent observation of a gamma-ray burst - supernova association is discussed by Lazzati et al.).

Where are their remnants (observation) and what properties do they have (theory)? What is the CR total-power and spectrum produced in these events in our and other galaxies?

2. There is solid observational evidence that spiral galaxies possess the extended, thermal, magnetized halo or “corona” originally introduced by Spitzer, that our Galaxy forms no exception and that these halos are in a very dynamic, turbulent state.

Where and with what total power are particles accelerated in these halos?

3. What is the total cosmic-ray power of our Galaxy?

If the answer turns out to be significantly higher than the standard value of $1.5 \times 10^{41}$ erg/sec (as recently advocated by Dar & De Rújula) a similar upscale is necessary for other galaxies. With an increase by more than a factor 10 CR pressure is expected to dominate the thermal gas pressure in the center of galaxy clusters. This would refute extension of an already relatively long manuscript and reasoned: “Dr. Plaga argues that 15 A & A pages is quite a lot, but he is trying to challenge the cosmic ray edifice that stands upon uncounted thousands of pages, articles, and conferences?”. Moreover in none of two recent reviews of CR origin any alternative in the sense of section 5 is mentioned, though in both cases such alternatives were presented at the corresponding conferences.

27 Because VHE astrophysics lacks sensitive all-sky detectors, it seems likely that the objects will eventually be discovered in the X-ray.

28 A consideration of various anomalous non-thermal remnants in our Galaxy might be interesting in this connection.
one of the strongest arguments\cite{2} against “MOND”, Mordehai Milgrom’s modified Newtonian dynamics\cite{72}.

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Figure 1: The flux of hadronic CRs rays as measured by various experiments as a function of total energy. The faint dashed line through all the data is a power law with a constant index of -3, and demonstrates that a single power-law is an excellent first-order approximation to the experimental data over the whole energy range. The deviation from a power law at energies below 10 GeV is due to solar and terrestrial modulation effects. The basic components of the experimental CR spectrum in the “eclectic (many source classes)” scenario, generally accepted presently, are sketched. More than four decades have passed since P. Morrison suggested a slightly different “hierarchical” framework[76], in which cosmic-rays fill increasing shares of the universe with increasing energy. From the lowest energies up to the “knee” at $4 \times 10^{15}$ eV SNRs are the main contributors (full line). Theoretical arguments and experimental evidence suggest an earlier cutoff around $10^{14}$ eV, this is symbolized together with the question marks. At higher energies up the the “ankle” at about $5 \times 10^{18}$ eV another source class of unclear nature, labeled here with “Unknown sources” (dashed line) takes over. At still higher energies an extragalactic component (dash-dotted line) dominates, that is expected to cut off at the so-called “Greisen limit” of $5 \times 10^{19}$ eV (the fact that the observed spectrum shows no evidence for such a cut-off is symbolized by the question marks). The missing cut-offs and exceptionally smooth joints of the three components (in particular at the “knee”) finds no natural explanation at the moment. The idea that this theoretical patchwork does not do justice to the impressing simplicity and unity of the experimental data strongly suggests itself. It seems more reasonable to posit that the “Unknown sources” component dominates the hadronic CR luminosity at all energies. (Figure modified from an original of S.P.Swordy)
Figure 2: This X-ray image of the Cassiopeia A (Cas A) supernova remnant is the official first light image of the Chandra X-ray Observatory[30]. The 5,000 second image was made with the Advanced CCD Imaging Spectrometer (ACIS). Two shock waves are visible: a fast outer shock and a slower inner shock. The inner shock wave is believed to be due to the collision of the ejecta from the supernova explosion with a circumstellar shell of material, heating it to a temperature of ten million degrees Celsius. The outer shock wave is progressing into the normal interstellar medium. The bright object near the center may be the long sought neutron star or black hole that remained after the explosion that produced Cas A.
Figure 3: The region around DR4 in the light of 92 cm radio waves (left image, from the WENSS survey \cite{115}) and 100 µm infrared light from the IRAS ISSA server \cite{61}. The radio image indicates the distribution of relativistic electrons emitting synchrotron radiation in the magnetic field of a molecular cloud compressed by the SNR shock wave. The infrared emission traces dust in the cloud heated by the passage of the shock wave. The similar distribution of both is an argument in Cavour of an interaction of shock wave and cloud. Both frames are untreated 1-degree cutouts from the respective cataloguers. They are centered on the coordinates ra: 20h 22m 37.98s; decl: +40d 09m 41.0s (J 2000).
Figure 4: Various experimental upper limits on the flux of VHE $\gamma$-rays from the region DR4 in the SNR G78.2+2.1 are compared to a theoretical prediction, derived under the assumption that SNRs are the main sources of hadronic rays (from the thesis of Prosch which contains all the references.) The predictions under the assumption of two spectral power-law indices of the accelerated hadrons $-2.1$ (full line) and $-2.3$ (dashed line) are shown. The universal value for strong shocks theoretically expected is $-2.1$. A spectral cutoff at 100 TeV was also assumed. The detailed assumptions used for deriving the theoretical curves are explained in Prosch et al. This publication contributed the point labeled “AIROBICC 1996” and was the first to officially announce the failure of the theoretical predictions by Aharonian et al.
Figure 5: Radial distribution of 3 GeV protons at $z = 0$, for diffusive reacceleration model with different halo sizes $z_h = 1, 3, 5, 10, 15,$ and $20$ kpc (five continuous solid curves). The source distribution assumed for the calculation of these curves is that for SNRs as given by Case & Bhattacharya [25], shown as a dashed line. The cosmic-ray distribution deduced from EGRET $>100$ MeV gamma rays [99] is shown as the histogram. It is seen that the distribution of hadronic cosmic rays is essentially homogenous up to about 15 kpc. If cosmic rays are mainly produced in SNRs or similarly distributed objects a strong concentration towards the Galactic center is expected - in strong contradiction to the data. (Figure taken from Strong and Moskalenko [101].)