Galactic cosmic rays

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Abstract. In this brief review we describe the theory of the origin of Galactic cosmic rays. The concept that interaction near the source is the dominant source of γ-rays, and spallation secondaries seems best suited to explain the EGRET γ-spectrum of the inner Galaxy, the abundances of light elements, the anti-protons and the positrons. Also the chemical abundances seem best described as resulting from the chemical composition of massive star winds. This leads to a supernova mechanism, long known, that the magneto-rotational mechanism provides the energy, about 10^{52} erg, for the explosion of the most massive stars; this mechanism naturally allows to understand jet-supernovae and Gamma Ray Bursts from its underlying symmetry. A key theoretical question remains open: the role of magnetic fields, both in the transport of cosmic rays in the Galaxy, as well as in the enhancement they may get in shock waves on various length scales, either starting with existing magnetic fields, or starting from electric current systems. An ultimate hope and expectation obviously is, once we understand the origin and physics of cosmic rays, to turn them into a tool to understand to understand the nature of matter at a yet deeper level.

1. Introduction

The basic concepts that we adopt when explaining the energies and spectra of Cosmic Rays, are a) the energy derives from supernova explosions (early 1930ies Baade & Zwicky), and b) the particle acceleration is done in shock waves, caused by these supernova explosions (E. Fermi, 1949 and 1954; A. Bell, I. Axford *et al* , R. Blandford & J.P. Ostriker, G. Krymskii *et al* , all 1977 and 1978). The major progress has come from discussing in detail how this acceleration works in the shock waves, and also from detailed observations at many particle energies, many isotopes of various nuclei, and at many wavelengths, with especially important observations in the photon GeV region, and lately in TeV γ-rays.

The main approach used to be that acceleration and propagation is mostly happening in the interstellar medium, but over recent years it has been recognized that much of the interaction is happening in the environment of the exploding star; in fact, the nature of the exploding stars, and their pre-explosion environment has been key for some attempts to make quantitative predictions. Some of these predictions have been successfully verified.

However, although many ideas have been proven to be correct, and a number of concepts and simulations have failed, a final judgement is still premature at this time, on how Nature is doing it.

2. Spectrum and knee

An energetic particle, which is just slightly suprathermal can be kicked across the shock, then gets isotropized in its meandering, and goes back, gaining typically a small fraction of energy each time. This is called Fermi acceleration after its discoverer (1949 and 1954), and the variant using shockwaves was almost simultaneously discovered by A. Bell, I. Axford *et al* , R. Blandford & J.P. Ostriker, and G. Krymskii *et al* (1977, 1978). Work by R. Jokipii, A. Meli and others has shown that the rate of acceleration can be much larger in highly oblique shock waves. A. Meli (2004, 2005) has demonstrated, that the distribution of the individual gain steps is no longer a narrow tight Gaussian around U_{sh}/c, but a broad powerlaw tail extending to fractional gains exceeding unity; here U_{sh} is the shock velocity. Despite these very different single energy gain steps, the resulting spectrum is unchanged, and just given by the density jump across the shock.

Considering then a shock running through a stellar wind, the final cosmic ray spectrum is modified by a number of effects:

The first and most important effect is that in a decreasing density outwards, the shock does not slow down, quite opposite to the behaviour in the interstelllar medium. So the entire acceleration episode is over fast. This has an important bearing on the observability; the probability to catch a supernova shock racing through a stellar wind is miniscule in a normal galaxy, while the ever slowing shock of a supernova remnant expanding into the interstellar medium takes a really long time. Therefore most of the observed supernova remnants in our Galxy are explosions into the interstellar medium. We have to look at the starburst galaxy M82 to observe wind supernova explosions (work with P.P. Kronberg, already since the late 1970ies).

The next effect is that the chemical composition is that of the stellar wind, near the end of their star's lifetime heavily enriched. And the injection history implies that the rate of injection scales with the ambient density, so in a wind with radius as r^{-2}.

As the shock system expands, it suffers adiabatic losses; these losses compete with the energy gains upon each cycle of a particle going back and forth across the shock. This loss is of course only important when the time scale going back and forth is a reasonably large fraction of the expansion time scale, so it does strongly depend on the scattering coefficient.

An important aspect of the magnetic field is that the field is a Parker type spiral (1958), so the magnetic field is almost perfectly perpendicular to the shock normal, modifying the rate of acceleration, as mentioned already above. Seen from the moving shock frame then yields an electric field, which in turn gives an additional motion, and a drift acceleration, since the drift - a Crab-like sideways walk in curved magnetic field - is parallel to the electric field. Now we also know that cosmic ray laden shocks are unstable, and if we did not know this from theoretical analyses, the observations of, say, Cas A, show convincingly a very large disturbance, with the turbulent velocity components equal to the overall expansion speed. This entails that the dominant scattering or transport of energetic particles is by these turbulent bubbles, and the dominant drift energy gain is in the curvature of the magnetic field in these bubbles. This drift energy gain depends on the scale of the curvature, and so introduces a length scale into the acceleration system.

Using then well-known concepts from the theory of turbulence, we proposed the principle of the smallest dominant scale (1993), taking it for both length as well as velocity scales, to construct a transport coefficient. We started here with Prandtl and Karman. This scattering or transport coefficient is used to evaluate the time scale a particle spends on either side of a shock, and so to give the adiabatic loss accompanying the gain; the length scale is also used for the drift curvature gain.

In a Parker magnetic field topology in a stellar wind then also gives two limits for the acceleration rate, near the pole, where the magnetic field is mostly radial, and over most of 4π where the magnetic field is mostly tangential to the shock surface. Matching these two regimes gives a critical energy of

$$E_{knee} \simeq Z\, e\, B(r)\, r\, (\frac{v_{sh}}{c})2 \tag{1}$$

which we identify with the knee (we ignore here a factor of order unity for clarity). The limit of acceleration is then clearly a similar expression:

$$E_{ankle} \simeq Z\, e\, B(r)\, r \tag{2}$$

First we note that these two energies are constant throughout a Parker limiting regime, since there the dominant magnetic field is the ϕ-component, which runs as $1/r$.

As can be shown (1993), the drift energy gain component is also modified at the same rigidity, and so the spectrum is slightly steeper beyond this energy.

However, these expressions hold for a single supernova explosion, and so this scheme requires, perhaps implausibly, that all stars that contribute, have the same basic properties at the end of their lives, notably the same magnetic field, and implicitly the same rotation, and explosion energies. This is only possible and plausible for the magneto-rotational mechanism of the supernova explosions, proposed specifically for supernovae by G. Bisnovatyi-Kogan (1970), following an earlier suggestion by N. Kardashev for supernova remnants (1964). However, this is fully consistent with present day knowledge of what massive stars do, and today is the only proven explosion mechanism, that actually works and is published.

The cosmic ray spectrum that had been predicted on this basis, $E^{-7/3}$ is very close to what has since been demonstrated.

3. Propagation

Propagation is perhaps the most contentious of the cosmic ray arguments.

The observed high energy electron spectra are $E^{-10/3}$, are obviously in the loss domination regime by synchrotron and inverse Compton losses, and so following N. Kardashev (1962) the injection has been with $E^{-7/3}$. At lower energy the electrons have a $E^{-8/3}$ spectrum, observed all across any well observed galaxy (work y R. Beck *et al* , and E. Berkhuijsen *et al* , and others). Clearly the difference to the inferred injection spectrum corresponds well to a diffusion time scale energy dependence derived from a Kolmogorov law $\tau_L \sim E^{-1/3}$. In fact, all interstellar medium data obtained in other regimes and wavelengths suggest very strongly a Kolmogorov law of turbulence, despite all the caveats about anisotropic turbulence. We can check our thinking about turbulence in the Solar wind (see, e.g., the work by W. Matthaeus).

This entails a critical difficulty, compared to previous considerations in cosmic ray physics: The Boron/Carbon ratio as a function of energy should also reflect this energy dependence, $E^{-1/3}$, but this is in blatant conflict. This can be resolved, and actually led a prediction (1997 and 1998), therafter verified, about the interaction in the source region. The turbulence spectrum excited by the cosmic ray laden shock corresponds to a diffusion coefficient energy dependence of $E^{-5/9}$, and this was subsequently confirmed with an elegant test by V. Ptuskin (1999), who found the best fit to the data as $E^{-0.54}$.

Another difficulty is the earlier thinking, that the knee is a transport effect; the transport of cosmic ray particles is modified at a specific rigidity. This would entail, that the interstellar medium has a special scale, at the diffusion scale at the knee energy. Sofar such a scale has not been identified in the interstellar medium, and one would expect in the case of such a change in energy dependence that the anisotropy of the cosmic rays at a rather higher energy would be noticeable, and it is not - at least not sofar. Also, in the case of a scale change in transport one might expect that the knee would be very smooth, and not just a the limit of sharpness conceivable for a 3D plasma.

4. Abundances

A shock that accelerates cosmic rays picks up the abundances of the material it is running through. In the interstellar medium, that is obviously the normal abundances, and in a stellar wind, it is the heavily enriched abundances prevalent in the wind of very massive stars at the end of their spectacular life; the wind mass loss is so large that the deeper layers, full of the the nuclei resulting from nuclear burning are exposed. It is important to realize that the abundances of the pre-explosion wind are relevant, not the abundances of the remnant itself, as the shock races far ahead of the piston constituted by the final remnant.

One aspect that is only slowly finding an understanding, is the effect of the initial ion charge: In a stellar wind, some ions are doubly ionized and others are singly ionized; this is clearly an effect of the radiation field and temperature in these winds. In the first injection step this charge $Z_{i,inj}$ of ion i plays an important role, and so ions which are doubly ionized, are much more easily injected. This translates into the so-called "first ionization potential" effect. A second, more subtle effect is the effect of the fully ionized charge Z_i of an ion, since the momentum distribution of the energetic particles couples to a basic wavelength, which is probably common to all ions: so the charge Z_i introduces an additional effect (work with A. Popescu).

One consequence is that the explosion of the really massive stars happens with 10^{52} erg (work with G. Pavalas). This can be derived from the number of such stars, with enriched abundances, and the heavy element abundance, such as Carbon, in the cosmic rays. The topology of a magneto-rotational explosion is also just what is seen in Cas A in X-rays. This then is a hypernova, as so dubbed by B. Paczynski, and leads directly to jet-supernovae (A. Heger *et al*) and Gamma Ray Bursts.

For the detailed abundances in cosmic rays, we have to differentiate between the various evolution stages, and final stages:

First, those stars that do explode into the interstellar medium, and start on the zero-age-main-sequence (ZAMS) between 8 and about 15 solar masses. These stars clearly inject interstellar medium abundances, and their cosmic rays interact in the interstellar medium only.

Second, stars in the zero-age mass range of about 15 to about 25 solar masses; these stars have a strong wind, but the deeper layers exposed are mostly enhanced in Helium; the wind is strong, but not strong enough to push far out, about 0.1 parsec. This means that the acceleration of the particles in the shock does not quite reach the geometrical maximum possible, imposed by the scale of the Larmor motion. These stars explode as Red Super Giant stars, RSG stars.

Third, the even more massive stars, above about 25 solar masses: These stars have a heavily enriched wind, and these stars provide all the heavy elements in cosmic rays (work with A. Popescu). These stars explode as Wolf-Rayet stars, WR stars. And it is the scarcity of these stars, that leads to the implication mentioned above that these stars explode with rather more energy, with about 10^{52} erg.

Judging then from the observed abundance distribution of cosmic rays, we may ask, what fraction of each element derives from which of these three populations of stars? The answer is probably, that about 2/3 of all Hydrogen derives from the first group. Helium mostly from the second group, and the rest of the Hydrogen (work with E.-S. Seo and R. Sina). And the rest of the Helium and all heavier elements from the third group.

5. Interaction

The interaction of the cosmic ray particles happens in the interstellar medium, but also close to the star. In the interstellar medium the relevant diffusion occurs with an energy dependence of $E^{-1/3}$. We observe this interaction regime in the outer Galaxy through the GeV γ-ray specrum.

Massive star winds produce a shell of old wind material, surrounded by interstellar medium material, which could be contaminated from earlier supernovae in the same neighborhood. After all the active places of star formation look quite active, as in the Orion region in the Solar neighborhood, or the Cygnus region, a bit further away.

For the RSG stars the wind shell is not quite so massive, so that the interaction is dominated by convection, so no additional energy dependence is introduced. The resulting secondaries, be it positrons, anti-protons, or γ-ray photons from pion decay, are all injected with the same spectrum as the cosmic rays, so $E^{-7/3}$. This is what we observe in the EGRET spectrum of the inner Galaxy.

For individual sources there could also be an emission from the pion decay leptons: The source is $E^{-7/3}$ protons and other nuclei. The interaction produces electrons and positrons with the same spectrum basically. They could be loss dominated, and so immediately turn into a $E^{-10/3}$ spectrum, give synchrotron and inverse Compton emission, a spectrum in photons of $E_{\gamma}^{-13/6}$, fully consistent with the recent HESS data.

For the WR stars the wind shell is very massive, and so we posit that the transport is diffusive, and so as excited by the cosmic ray spectrum itself, with an additional energy dependence of $E^{-5/9}$ (work with N. Langer, E.-S. Seo, and T. Stanev). This entails a contribution in positrons, anti-protons, and the γ-ray spectrum correspondingly steeper.

The pion decay emission argument can be repeated for WR stars (work with T. Stanev and P. Lipari).

The real test is the inner and outer Galaxy, as published by S. Casanova *et al* (2004). This simulation reproduces the inner Galaxy spectrum, dominated in this concept by the interactions near the RSG stars, and so quite flat. HESS data of the innermost Galaxy indicate quite clearly consistency with this spectrum as well, as recently shown at various meetings. The simulation shows that in the outer Galaxy the ISM interactions dominate, and so give the spectrum as expected, and confirmed by MILAGRO data. The latitude distribution of the emission is a second test.

We have shown using the published and available KASKADE data, that the picture is also fully consistent with those muon and electron/positron distributions, both as a function of shower inclination and of shower energy (work with S. Ter-Antonyan, and A. Vasile). This result is independent of the Monte-Carlo used.

So obviously this model predicts that the TeV emission should be quite patchy, and the maximum energy from the RSG stars should give a sharp turnoff in the γ-ray spectrum of the Galaxy at higher energies.

6. Magnetic fields

The origin of the cosmic magnetic fields continues to elude us. There are a number of concepts, some of them well tested, but usually found to be too slow.

The old approach was to use the battery mechanism (1950) to create weak fields in the galaxy, and then strengthen them with a dynamo process, over long times. Since the dynamo process, the rising of a magnetic loop, twisting it, and folding it back down, is a slow diffusive process, the observations clearly demonstrate that it is too slow (R. Kulsrud). A cosmic ray driven dynamo is still too slow, because it operates on the rotation time scale at best (H. Lesch *et al*). The destruction time scale of the magnetic field order is a small fraction of the rotation time scale, and so we do require a mechanism which is faster. Using Maxwell's laws to infer the required conditions leads to the speculation, that perhaps large scale shocks provide two dimensional electric currents, vertical sheet currents (work with C. Galea, A. Kandus, P.P. Kronberg, V. Curtef); if such currents were to exist, then a lowest order constant large scale magnetic field could be provided.

Matching the HESS and other data for young supernova remnants implies that the magnetic field is considerably enhanced in shocks (work by Völk *et al* , on Cas A and other young supernova remnants), perhaps by local instabilities (A. Bell 2004, 2005, P. Blasi *et al* , 2005), or perhaps by electric current systems. This may imply the same requirement as the symmetry argument from the overall magnetic field in galaxies (P. Biermann and collaborators; ongoing work with A. Kandus).

This serious lack of understanding stymies us in our attempt to fully comprehend the acceleration and the transport of cosmic rays; this is the major missing link at present, I think.

7. Critical tests

The standard picture of cosmic ray transport is unable to reproduce the γ-ray spectrum, the anti-proton and positron spectrum, and has been used by some to argue that we require special supersymmetric particles to explain these data. We have shown, that by Occam's razor a simpler theory can successfully explain all these data, just taking more of the stellar physics into account. We are not finished in performing all the tests, but all tests that we have done have been encouraging.

This proposal leads to the clear expectation, that the TeV γ-ray emission is quite patchy, and shows a turnoff at some higher photon energy, when the RSG stars run our of acceleration power, and the steeper spectrum WR stars take over. There should be patches of emission corresponding both to RSG as well as WR stars (work with T. Stanev and P. Lipari).

The abundances in cosmic rays should fully correspond to a proper integral over all contributing stars, that do explode, with the abundances taken from the injection site, the expanding shock wave (work with A. Popescu). This requires knowledge of the explosion energy.

These proposals clearly correspond to older idaes about the WR stars injecting some isotopes into the cosmic rays.

This proposal also solves the problem of the light spallation elements in the young Galaxy, as noted by H. Reeves (2005). The spallation happens in a heavily enriched environment, quite independent of what the outside abundances are, or were.

XTE 1550-564 has a spectrum of $\nu^{-0.66 \pm 0.005}$ (S. Corbel et al. 2002), corresponding to a particle spectrum of $E^{-2.32\pm0.01}$. This is consistent with a conical cut of a spherical geometry, and so the same scaling as in a wind shock acceleration, with $E^{-7/3}$. This is a test on the acceleration in curved geometries.

The γ-ray spectrum of outer Galaxy from GeV to TeV to PeV: The first MILAGRO results is consistent with $E^{-8/3}$, consistent with our model, which predicts that in the outer galaxy the interstellar medium interaction dominates. A much more extende and more precise spectrum would be useful.

The γ-ray spectrum of innermost Galaxy region from GeV to TeV to PeV: The first HESS spectrum of diffuse emission of a region very close to the center yields $E_{\gamma}^{-2.29\pm0.07}$; this confirms the wind model approach. The spectrum of a much wider longitude range would be highly desirable.

The neutrino spectrum of the inner Galaxy will be a beautiful test, the ultimate challenge for these ideas. The model predicts, obviously, a spectrum corresponding to $E^{-7/3}$.

Another forthcoming test will be the sky distribution of the arriving cosmic rays just in the transition region between the Galactic cosmic rays and the extragalactic cosmic rays (work with A. Bogdan). This will be doable with the AUGER measurements.

8. Advocatus diaboli

What leaves a deep uncertainty here?

The main problem that I feel with the picture is that we use on one side the supersonic turbulence picture to derive the transport coefficient, but on the other side actually use a smooth shock jump. Could it be that there is an isomorphic concept, in which the shock itself is unsteady, is sometimes strong, at other times not even there, much like the edge of the water from a dissipating wave on a beach, a beach where the waves start breaking at 2m height. Could it be that the particles go downstream just because the shock dissappeared, just to be swept up again in the next shockwave?

Also, is it really true that all stars die equally, at least all very massive stars?

Another point often made by H. Völk is that the spectrum of particles which we calculate is actually the one downstream, and so is part of a confined population, until everything is all over, and all those particles are injected into the outside environment. During this ejection of the population many things can happen, especially energy loss by adiabatic expansion.

Another difficulty is that we argue about supermassive star winds, and yet know that a good fraction of these stars are in binary systems.

On the other hand, the rare explosions of supernova type Ia, now so famous as cosmological standard candles, is an additional component of shock waves in the interstellar medium, and so another injector of interstellar medium material, all caused by low mass stars.

9. Conclusion

The standard transport model is unable to explain key data without invoking new particles. A model which includes interaction near the injection site is fully capable to explain the data. For a number of quantitative predictions the tests were encouraging.

The role of the magnetic field still eludes us.

Goaded and guided by the new high precision data of abundances at high particle energy on one side, and by the beautiful γ-ray data on the other we hope to come to a full understanding of the origin of Galactic cosmic rays, with the final tests probably coming from the AUGER and ICECUBE experiments.

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