CENTAURUS A: THE EXtragalactic SOURCE OF COSMIC RAYS WITH ENERGIES ABOVE THE KNEE

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ABSTRACT

The origin of cosmic rays at all energies is still uncertain. In this paper, we present and explore an astrophysical scenario to produce cosmic rays with energy ranging from below $10^{15}$ to $3 \times 10^{20}$ eV. We show here that just our Galaxy and the radio galaxy Cent A, each with their own galactic cosmic-ray particles but with those from the radio galaxy pushed up in energy by a relativistic shock in the jet emanating from the active black hole, are sufficient to describe the most recent data in the PeV to near ZeV energy range. Data are available over this entire energy range from the KASCADE, KASCADE-Grande, and Pierre Auger Observatory experiments. The energy spectrum calculated here correctly reproduces the measured spectrum beyond the knee and, contrary to widely held expectations, no other extragalactic source population is required to explain the data even at energies far below the general cutoff expected at $6 \times 10^{19}$ eV, the Greisen–Zatsepin–Kuz'min turnoff due to interaction with the cosmological microwave background. We present several predictions for the source population, the cosmic-ray composition, and the propagation to Earth which can be tested in the near future.

Key words: cosmic rays – galaxies: active – galaxies: jets – galaxies: starburst

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1. INTRODUCTION

Cosmic rays were originally discovered in 1912/1913 by Hess (1912) and Kohlhörster (1913) and still today we have no certainty where they come from. Their overall spectrum has been shown to be essentially a power law with a bend down near $10^{15}$ eV, called the knee, and a turn toward a new flatter component near $\sim 3 \times 10^{18}$ eV, called the ankle, with a final turnoff just around $10^{20}$ eV, as summarized in Gaisser & Stanev (2008).

It is thought that the component below about $3 \times 10^{18}$ eV is Galactic and the component above this energy is extragalactic on the basis that particles above such an energy would be hard to contain and isotropize in the magnetic fields in the interstellar medium (ISM) disk of the Galaxy. Different astrophysical scenarios have been proposed to explain the Galactic and extragalactic components of the cosmic radiation; see the overview in Stanev (2010a, 2010b).

The basic paradigm for Galactic cosmic rays has been acceleration in the shock waves caused by supernova (SN) explosions (Baade & Zwicky 1934). The process of acceleration is diffusive shock acceleration (Fermi 1949, 1954) and it is based on the compression experienced by particles that get reflected by magnetic irregularities from both sides of a shock in an ionized magnetic plasma (Drury 1983). SNe are exploding stars and they may explode either directly into the ISM or into the stellar wind of the predecessor star (Woosley et al. 2002). Lagage & Cesarsky (1983) showed that acceleration at the shocks caused explosions into the normal ISM that cannot reach even the energies at the knee. Heavy nuclei can be accelerated up to about $10^{18}$ eV in Galactic sources, such as SN explosions of massive stars which explode into their wind (Völk & Biermann 1988), OB-star superbubbles, gamma-ray bursts (Dermer 2004) or micro-quasars, and active accreting black holes in stellar binary systems.

For higher energies ($> 10^{18}$ eV) extragalactic sources are the most accepted candidates. Nearby active radio galaxies with black hole activity were first proposed by Ginzburg & Syrovatskii (1963); see also, e.g., Lovelace 1976; Biermann & Strittmatter 1987) as possible sources. Gamma-ray bursts in other galaxies have also been suggested by Waxman (1995) and Vietri (1995). The radio galaxy Cent A is a prime example of a possible astrophysical source (Anchordoqui et al. 2011; Fargion & D’Armiento 2011). The interaction of high-energy particles with the microwave background limits the distance of the sources (Greisen 1966; Zatsepin & Kuz´min 1966; Allard et al. 2008; Stanev 2010b). For protons the energy at which the all-particle spectrum from many sources should turn off is estimated to be $6 \times 10^{19}$ eV and for other chemical elements the energy turnoff is lower (Allard et al. 2008). As the interaction distance becomes very large for particles with energy between $3 \times 10^{18}$ and $6 \times 10^{19}$ eV, the calculations predict that a large number of extragalactic sources contribute to the measured flux in this energy range. This is a primary prediction of these calculations.

Of special interest also is the transition from Galactic to extragalactic predominance which should happen in the energy range between $10^{16}$ and $10^{18}$ eV. Several experiments are presently taking data in this energy range: KASCADE-Grande, Telescope Array, IceTop, and the Pierre Auger Observatory. The transition is a very important feature because it is foreseen that breaks in the all-particle spectrum and in the composition can reveal the details of the particle production mechanisms, the source population, and propagation in the universe. There are a number of recent attempts to explain the cosmic-ray spectrum in the transition range, e.g., by Hillas (2006) and by Berezinsky (2009).

In this paper, we focus on the previously inaccessible continuous energy range above $10$ PeV extending to the highest energies
measured. Today it is possible to compare the predictions with high-precision data over the entire energy range. Therefore, it becomes important to have predictive power, i.e., to test quantitative hypotheses which were developed long before much of the new data were known.

We revisit here an idea originally proposed in 1993 (Biermann 1993; Biermann & Cassinelli 1993; Biermann & Strom 1993; Stanev et al. 1993) and we show how our Galaxy and the radio galaxy Cen A can describe the energy spectrum from 10 PeV up to $3 \times 10^{20}$ eV and describe the Galactic to extragalactic transition at the same time.

In the following sections, we first go through the tests the 1993 original model has undergone to date as regards spectra, transport, secondaries, and composition; second, we confirm the predictions of the original model with the newly available data beyond the knee energy, and finally we present the high-energy model which describes the transition between Galactic and extragalactic cosmic rays.

## 2. ORIGINAL MODEL AND ITS TESTS TO DATE

In a series of papers started in 1993 (Biermann 1993; Biermann & Cassinelli 1993; Biermann & Strom 1993; Stanev et al. 1993; Biermann 1994) an astrophysics scenario was proposed which emphasized the topology of the magnetic fields in the winds of exploding massive stars (Parker 1958). In Stanev et al. (1993), a comprehensive spectrum was predicted for six element groups separately: H, He, CNO, Ne–S, Mn–Cl, and Fe. The key points of this original model are as follows. (1) The shock acceleration happens in a region which is highly unstable and shows substructure, detectable in radio polarization observation of the shock region, which is also found in theoretical explorations (e.g., Bell & Lucek 2001; Caprioli et al. 2010; Bykov et al. 2011). Therefore, the particles go back and forth across the shock gaining momentum, while the scattering on both sides is dominated by the scale of these instabilities, which are assumed to be given by the limit allowed by the conservation laws of mass and momentum. (2) There are cosmic-ray particles which get accelerated by a shock in the ISM, produced by the explosion of a relatively modest high-mass star or, alternatively, by a low-mass SN Ia. This is most relevant for hydrogen and less so for helium and heavier nuclei. (3) Heavy cosmic-ray nuclei derive from very massive stars, which explode into stellar winds already depleted in hydrogen, and also in helium for the most massive stars. These explosions produce a two-part spectrum with a bend that is proposed to explain the knee. In this scenario, the knee is due to the finite containment of particles in the magnetic field of the predecessor stellar wind, which runs as $\sin \theta/r$ in polar coordinates (Parker 1958). Toward the pole region only lower energies are possible and the knee energy itself is given by the space available in the polar region. There is a polar cap component of cosmic rays associated with the polar radial field with a flatter spectrum. (4) Diffusive leakage from the cosmic-ray disk steepens all these spectra by $1/3$ for the observer. (5) Very massive stars eject most of their zero-age mass before they explode and so form a very massive shell around their wind (Woosley et al. 2002). This wind shell is the site of most interaction for the heavy nuclei component of cosmic rays. For stellar masses above about 25 solar masses in zero-age main-sequence mass (Biermann 1994), the magnetic irregularity spectrum is excited by the cosmic-ray particles themselves. The spectral steepening due to the interactions is $E^{-5/9}$ for the most massive star shells.

The final spectrum is a composite of these components; see Figure 1 of Stanev et al. (1993). The spectra predicted by these arguments match the data such as shown by the recent Cosmic Ray Energetics And Mass (CREAM) results (Wiebel-Sooth et al. 1998; Biermann et al. 2009). This scenario has undergone detailed tests as regards propagation and interactions (Biermann 1994; Biermann et al. 2009) so as to describe both Galactic propagation and the spectra of the spallated isotopes as well as the resulting positron spectra, the flatter cosmic-ray positron and electron data, the Wilkinson Microwave Anisotropy Probe haze and the spectral behavior of its inverse Compton emission, and the 511 keV emission from the Galactic center region. New Transition Radiation Array for Cosmic Energetic Radiation (TRACER) results (Obermeier 2011) are also consistent in terms of (1) the low-energy source spectrum, (2) the energy dependence of interaction, (3) a finite residual path length at higher energy, and (4) a general upturn in the individual element spectra. The newest Pamela results (Adriani et al. 2011) are also consistent with the 1993 original model in which hydrogen was the only element to have a strong ISM–SN cosmic-ray component, and so has a steeper spectrum than helium.

### 2.1. A Test Beyond the Knee

This original model was proposed to explain the particles observed above $10^9$ eV per nuclear charge. Here we first test the original model with the KASCADE data. The most accurate measurement of the energy spectrum in the knee energy range has been done by the KASCADE experiment (KASCADE-Grande Collaboration 2010). Figure 1 shows for the first time the comparison of the original model to the measured data from KASCADE. KASCADE reconstructs the spectrum using two hadronic interaction programs (QGSJet and Sibyll) in the analysis procedure. In the figure we show the data and the original model, and also include the ratio of the difference between original model and data divided by the experimental error. For the ratio shown we use only one of these interaction codes; as an example we use QGSJet. The figure shows good agreement between data and the original model to within the
errors of the data. This confirms the original model in the last remaining energy range where it had not previously been tested for lack of good data. This is the first key result of this paper.

2.2. Transport and Interaction Test

One question which invariably comes up is how this model deals with propagation and spallation. For this line of reasoning it is important to note two aspects: (1) plasma simulations, the deals with propagation and spallation. For this line of reasoning paper.

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...the interpretation that in an ionized magnetic plasma in near equipartition we have an approximate Kolmogorov spectrum (Kolmogorov 1941a, 1941b, 1941c) running without break from very large scales down to dissipation scale; (2) very massive stars eject most of the initial zero-age main-sequence mass in their powerful winds, which then builds up a correspondingly massive shell at the outer boundary of the wind. The cosmic-ray-loaded SN shock encounters and interacts with this massive shell.

All those cosmic-ray particles accelerated by an SN shock in the heavily enriched winds of Wolf–Rayet stars then excite magnetic irregularities, which can be described following Bell (1978a, 1978b); these self-excited irregularities describe the path of the cosmic-ray particles through the massive shell. This gives (Biermann 1998; Biermann et al. 2001) a boron/carbon ratio energy dependence of $E^{-5/3}$; this was found to be consistent with the data of Ptuskin et al. (1999), who determined $E^{-0.54}$. Since the straight-line path gives a minimum path, this model also gives a finite path length of interaction at high energy, consistent with the new data as noted above.

Other tests are as follows. The cosmic-ray electron spectrum has been determined to be $E^{-3.25 \pm 0.06}$ (Wiebel-Sooth & Biermann 1999) in the energy range up to a few TeV, a spectrum which is dominated by losses (Kardashev 1962). Therefore, the injection is with a spectrum flatter by unity. This has to be compared with the proton spectrum at a corresponding energy, which suggests $E^{-2.66 \pm 0.02}$ near TeV energies (Yoon et al. 2011); this spectrum has been steepened by the energy dependence of the diffusion, and so the difference to the inferred cosmic-ray electron spectrum gives this dependence as $E^{-0.43 \pm 0.06}$, consistent with $E^{-1/3}$ as deduced from the Kolmogorov assumption. Another consistency check is the timescale inferred at the highest energies for leaking out of the kpc-thick cosmic-ray disk near the Sun (Biermann 1993; Biermann & Cassinelli 1993; Biermann & Strom 1993).

Since we have about $10^7$ yr at GeV energies for protons, we infer with the Kolmogorov assumption a timescale of $10^{4.3}$ yr at $10^{17}$ eV—adopting the point of view that the highest energy cosmic-ray particles from the Galaxy are Fe (Stanev et al. 1993) at $10^{18.5}$ eV, matching in their scattering protons of $10^{17}$ eV; however, this is not yet finally settled.

This timescale is still significantly longer than the simple transit time across the thick disk of about $10^{4.3}$ yr, so that the isotropy observed can be understood without already invoking the effect of the Galactic wind. Using three times the simple transit time as the minimum to give isotropy we can invert this line of reasoning and deduce a maximum energy dependence of the scattering of $E^{-0.39}$ (Biermann 1993; Biermann & Cassinelli 1993; Biermann & Strom 1993), again under the assumption that the entire energy range is covered by the same power law.

The Wolf–Rayet star model is also able to explain the positron spectra and positron production (Biermann et al. 2009, 2010a, 2010b) as noted above.

3. THE HIGH-ENERGY MODEL

Based on the original model we propose here a high-energy model to explain the cosmic-ray data from 10 PeV to 300 EeV. We analyze the possibility that the very same spectrum proposed in 1993, however shifted in energy, can explain all the data up to 300 EeV including the knee region, the highest energy range ($>10^{18}$ eV), and at the same time the middle energy range ($10^{16}$ eV $< E < 10^{18}$ eV).

The cosmic-ray particles as seen in our Galaxy were argued to provide the seed particles for further acceleration to ultrahigh energy by a relativistic shock emanating from an active black hole in the nearby radio galaxy Cen A (Gopal-Krishna et al. 2010). This idea is explored here beyond what has been proposed in Gopal-Krishna et al. (2010), which demonstrated that Cen A can provide a sufficient flux for the highest energy particles by working out the energetic particle flux traversed by a shock surface in the jet of the radio galaxy Cen A with the one-step further acceleration in a relativistic shock as proposed by Achterberg et al. (2001). They used the spectral shape of the original model (Stanev et al. 1993) to fit the Pierre Auger data; however the fit of the measured spectrum was not constrained by the low-energy spectrum as proposed in the original model (Stanev et al. 1993).

The energy spectrum calculated here is simply a shift of the particle spectra proposed in the original model (Stanev et al. 1993) for low energies to the highest energies, preserving the relative abundances of the original model. This proposal is considerably stronger than the previous one presented in Gopal-Krishna et al. (2010). The energy shift corresponds to a factor of 2800 within the limits of a one-step acceleration by a relativistic shock as proposed by Achterberg et al. (2001). The original model (Stanev et al. 1993) has a number of parameters, which were set in 1992 (see Figure 6 in Stanev et al. 1993). None of these parameters had to be changed significantly in the analysis presented here.

4. MATCH TO DATA FROM 10 PeV TO 300 EeV

Finally, we can construct the energy spectrum of cosmic rays by adding the Galactic component to the extragalactic component as shown in Figure 1. In this figure, we show differential flux $\times E^3$ versus energy per particle as predicted by this analysis compared to the data from KASCADE (KASCADE Collaboration 2009), KASCADE-Grande (KASCADE-Grande Collaboration 2010), and the Pierre Auger Observatory (Pierre Auger Collaboration 2010a). In order to match the measurements from the two experiments, we have shifted, within the experimental uncertainties, the KASCADE and KASCADE-Grande flux down by 14% and the Auger flux up by 14%.

We distinguish six groups: H, He, CNO, Ne–S, Cl–Mn, and Fe. Particles were subjected to losses in the intergalactic radiation field (Allard et al. 2008). The numbers above the lines correspond to error estimations (Model – Data)/(Experimental Error). We note the good agreement between data and the model from below $10^{15}$ to $3 \times 10^{19}$ eV.

One extra assumption of the original model, namely the energy shift, allows a description of the energy spectrum above $10^{18}$ eV. Below the critical energy for interactions with the microwave background, it has been expected that we would
observe a very large number of sources at large distances. However, no other source population is needed to describe the energy spectrum above $3 \times 10^{16}$ eV. This is the second key new result of this paper.

To summarize, a few results can be extracted from the proposal here. (1) There are no other sources necessary to provide extra flux in the energy range $3 \times 10^{16}$ to $3 \times 10^{20}$ eV, the second key result of this paper. A detailed analysis of radio galaxies (Caramete et al. 2011) shows that the next strongest radio galaxy to contribute is Virgo A, as already predicted by Ginzburg & Syrovatskii (1963). We estimate the maximum possible extra flux from other sources within this distance limit at 0.1 in the log in Figure 1, so at 25%. We note that the self-consistent MHD simulations for cosmological magnetic fields presented in Ryu et al. (2008; see also Cho & Ryu 2009; Das et al. 2008) were carried out for protons, and so for heavy nuclei the magnetic horizon in intergalactic space is small, less than 100 Mpc consistent with the measurements of the Pierre Auger Observatory (Pierre Auger Collaboration 2010c) which suggest a heavier composition for energies above $10^{19}$ eV. However, at yet lower energies the sum of the more distant sources might exceed the flux predicted from single sources such as Cen A and Vir A; the magnetic scattering as predicted in Ryu et al. (2008; see also Cho & Ryu 2009; Das et al. 2008) seems to prevent this at all energies above the transition to Galactic cosmic rays. (2) The dip near $3 \times 10^{18}$ eV is explained by the switchover between the Galactic cosmic rays and the extragalactic cosmic rays (Rachen & Biermann 1993; Rachen et al. 1993). (3) The spectra of Galactic cosmic rays beyond the knee are adequately modeled by our approach, suggesting that the Wolf–Rayet star explosion model also matches the newest data beyond the knee. (4) There is no abrupt change in composition in the energy range from $3 \times 10^{16}$ to $3 \times 10^{18}$ eV.

In order to describe the data (Pierre Auger Collaboration 2010a) the high-energy model presented here requires minimal interaction along the path between the radio galaxy Cen A and us, and so indeed near-isotropic scattering in the magnetic wind of our Galaxy.

4.1. Isotropy?

The most recent results from the Pierre Auger Observatory indicate an excess in the direction of Cen A (Pierre Auger Collaboration 2010b) which might corroborate the analysis presented here. The Pierre Auger Observatory measures an isotropic sky for energies below $6 \times 10^{19}$ eV and a weakly anisotropic sky above this energy (Pierre Auger Collaboration 2010b). The isotropy for energies below $6 \times 10^{19}$ eV can be explained by a turbulent magnetic wind of our Galaxy (Everett et al. 2008). This wind is thought to be driven by cosmic rays and hot gas, and so is itself unstable, giving irregular magnetic fields, akin to radiation-driven winds of stars (Cassinelli 1994; Owocki 1990). The magnetic fields in the wind are strong enough to isotropize incoming heavy-element particles at very high energy and protons at lower energy. Scattering in a magnetic wind with $B_\phi \sim 1/R$ as a function of radial distance $R$ (Parker 1958) is strongly enhanced due to the extra factor derived from integrating the Lorentz force $\ln(R_{\max}/R_{\min}) \sim 5$. The maximal energy for total bending can then be given by the magnetic field strength (Everett et al. 2008) at the base $\sim 8 \mu$G, the length scale at the base $\sim 5$ kpc, the logarithmic factor $\sim 5$, and so is given by $10^{20.2} Z$ eV, where $Z$ is the charge of the cosmic-ray particle. Since at those energies the data measured by the Pierre Auger Observatory suggest that we actually have heavy nuclei, complete bending is assured. However, this would lead to a second problem in that we then might find a complete shielding for any particles coming from outside, so this magnetic wind must also have considerable irregularities; these irregularities in the wind need to be scale free (implying a saturated spectrum of irregularities or inverse cascade $I(k)k \sim$ constant, where $I(k)$ is the energy per wavenumber $k$ per volume), so as to avoid a characteristic energy below which all particles are cut off; or, if such an energy exists, it must be low enough not to disturb the spectral sum. The key point is that Parker winds (Parker 1958) are very effective at bending orbits. Obviously, the scattering might not be complete so that a small anisotropy is left, possibly explaining the Auger data clustering of events near the direction to the radio galaxy Cen A.

5. PREDICTIONS

Some predictions of the high-energy model presented here are as follows.

1. The calculations presented here predict the individual spectra for six element groups. The future data analysis from KASCADE-Grande, IceTop (Stanev 2009), Telescope Array, and the Pierre Auger Observatory will be able to test this prediction.

2. The trend to heavier nuclei from 2 to $6 \times 10^{19}$ eV has been suggested by measurements of the depth of shower maximum done by the Pierre Auger Observatory (Pierre Auger Collaboration 2010c); we caution that the interpretation of the data in terms of mass composition depends on hadronic interaction extrapolations.

3. An isotropic background contribution of high-energy cosmic rays from other more distant sources is compatible with our analysis up to 25% of the total flux.

An important caveat of the analysis refers to gamma-ray bursts. We could obtain similar results in describing the cosmic-ray spectrum if instead of exploding Wolf–Rayet stars we used gamma-ray bursts exploding into Wolf–Rayet star winds. This assumption allows that Wolf–Rayet star explosions might be due to the same mechanism as gamma-ray bursts, but just completely stifled by the mass burden, possibly implying the magneto-rotational mechanism of Bisnovatyi-Kogan (1970; see also Biermann et al. 2005; Bisnovatyi-Kogan et al. 2005). This would suggest that most Galactic cosmic rays should be attributed to gamma-ray bursts (Dermer 2004), and that the gamma-ray burst rate is substantially higher than heretofore believed. The predictive power for the spectral indices and the energy scales is lost in this alternative.

Finally, we show how the high-energy model proposed here could be falsified. (1) If all ultrahigh energy cosmic rays could be shown to be of one and only one chemical element, like all proton, or all iron. (2) If neutrino or gamma-ray data would unequivocally show that many nearby extragalactic sources contribute equivalently to the radio galaxy Cen A. This could occur naturally in a gamma-ray burst hypothesis, since many nearby starburst galaxies with high rates of star formation, SN explosions, and gamma-ray bursts could all contribute at comparable levels (Caramete et al. 2011). (3) If it could be clearly shown that the turbulent magnetic wind of our Galaxy does not have the required strength of magnetic field and spatial extent to affect near isotropy by magnetic scattering. (4) If an abrupt change of the composition is measured between the iron knee and the dip or ankle.
6. CONCLUSIONS

We conclude that our own Galactic cosmic rays plus the galactic cosmic rays from a radio galaxy shifted in energy in the relativistic shock of an accreting supermassive black hole reproduce the all-particle energy spectrum from $10^{15}$ to $10^{20}$ eV as measured by the KASCADE, KASCADE-Grande, and the Pierre Auger Observatories. In the scenario proposed here, no additional extragalactic source population for ultrahigh energy particles is required, contrary to many years of expectation. This implies that no other sources within the magnetic horizon are viable even at lower particle energies ($> 3 \times 10^{18}$ eV) above the switchover between Galactic and extragalactic cosmic rays.

The scenario proposed here gives a number of predictions, especially as regards the chemical element composition across this entire energy range. A detailed comparison of the measured and predicted composition is yet to be done. Once these predictions have been falsified or confirmed we will be closer to an understanding of the origin of cosmic rays 100 years after their discovery.

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