THE ENERGY PRODUCTION RATE DENSITY OF COSMIC RAYS IN THE LOCAL UNIVERSE IS 
\( \sim 10^{44} - 45 \) erg Mpc\(^{-3}\) yr\(^{-1}\) AT ALL PARTICLE ENERGIES

Boaz Katz\(^1\), Eli Waxman\(^2\), Todd Thompson\(^3,4\), Abraham Loeb\(^5\)

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Abstract

The energy output (per logarithmic interval of particle energies) of Cosmic Rays (CRs) with energies \( 10 \) GeV \( \lesssim \varepsilon_p \lesssim 100 \) GeV is \( \sim 10^{47} \) erg per solar mass of star—formation, based on the CR production rate in the Milky Way and in starburst galaxies, implying a generation rate of \( \varepsilon_p^2 Q \sim 10^{45} \) erg Mpc\(^{-3}\) yr\(^{-1}\) in the local universe. It is only \( \sim 10 \) times larger than the output, \( \varepsilon_p^2 Q = 0.5 \pm 0.2 \times 10^{44} \) erg Mpc\(^{-3}\) yr\(^{-1}\), of Ultra High Energy CRs (UHECRs) at energies \( 10^{15.5} \) GeV \( \lesssim \varepsilon_p \lesssim 10^{12} \) GeV (obtained assuming they are mostly protons), which in turn is comparable to the lower limit of \( \varepsilon_p^2 Q \geq 0.5 \times 10^{44} \) erg Mpc\(^{-3}\) yr\(^{-1}\) of high energy CRs with \( 10^6 \) GeV \( \lesssim \varepsilon_p \lesssim 10^8 \) GeV implied by the saturation of the Waxman-Bahcall bound by the neutrino excess recently discovered by IceCube. These similarities are consistent with a flat production spectrum, \( \varepsilon_p^2 Q \sim \text{const} \) for CRs at all observed energies. If a flat production spectrum is generated by our galaxy, the observed CR flux in the range \( 10^{6.5} - 10^{9.5} \) GeV, above the "knee", is suppressed compared to lower energies due to propagation effects rather than acceleration upper limits. As suggested by Parizot and Aublin, the most exciting possibility is that cosmic rays at all energies are emitted from a single type of (unknown) sources, which can not be supernova remnants.

Subject headings: cosmic rays

1. INTRODUCTION

The origin of the observed Cosmic Rays (CRs) at different energies is still unknown (see Blandford & Eichler 1987; Axford 1994; Nagano & Watson 2000; Helder et al. 2012; Lemoine 2013 for reviews). The energy density (per logarithmic particle energy) changes by about 8 orders of magnitudes across the observed particle energy range of \( 10^6 \) eV—\( 10^{20} \) eV. The cosmic ray spectrum steepens around \( 5 \times 10^{15} \) eV (the "knee") and flattens around \( 5 \times 10^{16} \) eV (the "ankle"). Below the knee the cosmic rays are thought to originate from Galactic supernovae. Above the ankle, the so called Ultra High Energy CRs (UHECRs) are believed to be of extra-Galactic (XG) origin since they cannot be confined by the galactic magnetic field and their measured flux is nearly isotropic.

In this letter we use current data to estimate the production rate of CRs in the local universe at the different energies and show that CRs of all observed energies may be produced with a universal flat energy production spectrum \( \varepsilon_p^2 d\varepsilon_p/d\varepsilon_p \sim \text{const} \). A softer universal production spectrum was suggested by Parizot (2003); Aublin et al. (2005) with a production rate of low energy CRs which is 1000 times larger than UHECRs. We resolve the differences and show that the softer spectrum found by these authors is due to over(under)estimates of the energy production rates at low(high) energy.

2. ENERGY PRODUCTION RATES AT LOW, INTERMEDIATE AND ULTRA-HIGH ENERGIES

If CRs at all energies are produced in galaxies, the observed flux of CRs at low energies is enhanced by several orders of magnitude due to the confinement of these CRs in our galaxy (Loeb & Waxman 2002) and the CR production spectrum is much harder than the observed spectrum. We next provide estimates for the production of CRs at the different energies for which we have reliable constraints. The estimates are summarized in figure 1.

2.1. UHE energies, \( \varepsilon_p \sim 10^{19} - 10^{21} \) eV

Consider first the energy production of the highest energy cosmic rays, \( \varepsilon_p \sim 10^{19} - 10^{21} \) eV. The distance of the extra-galactic sources of the observed CRs in this range is limited by propagation losses due to the interaction with the inter-galactic radiation field. The composition is controversial, with air-shower data from the Fly’s Eye, HiRes and Telescope Array observatories suggesting a proton dominated composition (Bird et al. 1993; Abbasi et al. 2010; Sagawa 2011) while the Pierre Auger Observatory suggesting a transition to heavy elements above \( 10^{19} \) eV (Abraham et al. 2010). Due to this discrepancy, and due to the experimental and theoretical uncertainties in the relevant high energy particle interaction cross sections used for modeling the shape of the air showers, it is impossible to draw a definite conclusion regarding composition based on air-shower data at this time. It should be noted that the anisotropy signal measured at high energies, combined with the absence of this signal at low energies, is an indication for a proton dominated composition at the highest energy.

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1 Institute for Advanced Study, Einstein Drive, Princeton, New Jersey, 08540, USA
2 Particle Physics & Astrophysics Dept., Weizmann Institute of Science, Rehovot 76100, Israel
3 Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH, 43210, USA
4 Center for Cosmology & Astro-Particle Physics, The Ohio State University, 191 West Woodruff Ave., Columbus, OH, 43210, USA
5 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

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where $\xi_z$ is a dimensionless parameter of order unity, which depends on the redshift evolution of $\varepsilon_p^2 Q$.

The neutrino excess cannot originate from interaction of cosmic-ray protons with interstellar gas in the Galaxy, which produces an average (over angles) intensity of $\Phi_{\nu} \approx 1 \times 10^{-6} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (e.g. Waxman & Bahcall 1999), implying a lower limit on the energy production of the CRs which produce these neutrinos. We next briefly describe this constraint. For a more detailed discussion, see (Spector et al. 2013).

The IceCube collaboration has recently reported the detection of 26 neutrinos in the energy range of 50 TeV to 2 PeV, which constitutes a 4$\sigma$ excess above the expected atmospheric neutrino and muon backgrounds (Kopper et al. 2013). The excess neutrino spectrum is consistent with $d\Phi_{\nu}/d\varepsilon_{\nu} \propto \varepsilon_{\nu}^{-2}$, its angular distribution is consistent with isotropy, and its flavor ratio is consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. We stress that the spectral shape, angular distribution and composition are currently poorly constrained due to the low statistics. The best fit normalization of the intensity is $\varepsilon_p^2 \Phi_{\nu} = 3.6 \pm 1.2 \times 10^{-8} \text{GeV/cm}^2\text{sr}$, coinciding (in normalization and spectrum) with the Waxman-Bahcall (WB) bound on the neutrino intensity that may be produced by extra-Galactic sources (Waxman & Bahcall 1999).

\begin{equation}
\varepsilon_p^2 \Phi_{\text{WB}, \text{all flavor}} = 3.4 \times 10^{-8} \frac{\text{GeV}}{\text{cm}^2\text{sr}} \times \frac{\xi_z}{3} \times 0.5 \times 10^{44} \text{erg Mpc}^{-3} \text{yr}^{-1}
\end{equation}

where $\varepsilon_p^2 Q$ is the UHECR proton production rate, and $\xi_z$ is a dimensionless parameter of order unity, which depends on the redshift evolution of $\varepsilon_p^2 Q$. The value $\xi_z = 3$ is obtained for redshift evolution following that of the star-formation rate or AGN luminosity density, $\Phi(z) = (1 + z)^3$ up to $z = 2$ and constant at higher $z$ ($\xi_z = 0.6$ for no evolution).

The neutrino excess cannot originate from interaction of cosmic-ray protons with interstellar gas in the Galaxy, which produces an average (over angles) intensity of $\approx 10^{-9} (\varepsilon/100\text{TeV})^{-0.7} \text{GeV/cm}^2\text{sr}$ (based on the Fermi determination of the $\pi_0$ decay intensity at 100 GeV (Ackermann et al. 2012) and the Galactic CR spectrum $\varepsilon_p^2 d\Phi/d\varepsilon \propto \varepsilon^{-0.7}$). It is also unlikely to be due to (unknown) Galactic sources, which are expected to be...
They are proportional to the star formation rates (see dispersion in the local universe by assuming that the rate in the Milky Way (MW). The starburst/MW CR emission), and the other based on the CR production different ways. One based on the CR production rate in the Milky Way (MW) and in which CRs lose most of their energy to pion production be- option, sources with observed flux and spectrum. We thus consider the former perspective of the synchrotron and the gamma-ray emission of M82 and NGC 253, which imply $\nu_{\text{sync}} \sim 0.2$ (assuming that the observed gamma-ray flux is dominated by $\pi_0$ decays Lacki et al. 2011; Thompson & Lacki 2013). The FIR luminosity is, in turn, related to the SFR by $L_{\nu}\sim 7 \times 10^{39}$ erg$/M_{\odot}$, with a $50\%$ uncertainty [Yun et al. 2001; Kennicutt 1998]. Using $L(8-1000\mu m)/L(\nu=1.4\text{GHz}) = 1.3$ [Yun et al. 2001], we find

$$\varepsilon_2^p Q_{(10\text{GeV})}/SFR \approx 4 \times 10^{46} \left(\frac{0.3}{\nu_{\text{sync}}}\right) \text{erg}/M_{\odot}. \quad (4)$$

Equivalently, a similar value can be obtained for M82 and NGC 253 by directly comparing their gamma rays to their FIR luminosities. The ratio of observed gamma-ray to FIR luminosities of both galaxies is $\nu L_{\nu}(\text{GeV})/L_{\nu}\approx 1.3\epsilon - 5$ [Ackermann et al. 2012] leading to CR efficiencies of $\varepsilon_2^p Q_{(10\text{GeV})}/SFR \approx 3 \times 10^{46}$ erg$/M_{\odot}$, where we assumed that $1/3$ of the energy carried by $10^{16}$ GeV CRs is converted to ~ GeV $\gamma$-rays.

Using the local SFR density, $\dot{\rho}_{\text{SFR}}(z = 0) \sim 0.015 M_{\odot}$ yr$^{-1}$ Mpc$^{-3}$ (e.g. Hopkins & Beacom 2006), we thus find

$$\varepsilon_2^p Q_{(10\text{GeV})} \sim 0.6 \times 10^{45} \text{erg Mpc}^{-3} \text{yr}^{-1}. \quad (5)$$

Note that if CRs are assumed to be produced by SNe, then eq. (4) and the number of SNe per stellar mass produced, ~ $10^{-2}/M_{\odot}$, imply $\varepsilon_2^p d N_p/d \epsilon_p \sim 6 \times 10^{48}$ erg per SN.

We next estimate the production rate of the same CRs by relating it to the total estimated production in our galaxy. Normalizing to the SFR, the production rate of CRs with energies $\epsilon_p \sim 10^{10} - 10^{11}$ eV can be estimated by

$$\varepsilon_2^p Q_{(10\text{GeV})}/SFR \sim \frac{\varepsilon_2^p Q_{\text{MW}}}{\text{SFR}(\text{MW})} \sim 2 \times 10^{47} \text{erg}/M_{\odot} \quad (6)$$

or

$$\varepsilon_2^p Q_{(10\text{GeV})} \sim 3 \times 10^{45} \left(\frac{\epsilon_p}{10 \text{GeV}}\right)^{-0.25} \text{erg Mpc}^{-3} \text{yr}^{-1} \quad (7)$$

where $\text{SFR}(\text{MW}) \sim 2 M_{\odot}$ yr$^{-1}$ is the current star formation rate in the Milky Way [e.g. Chomiuk & Povich]
and \( \varepsilon_p^2 Q_{MW} \sim 4 \times 10^{47} (\varepsilon_p/10 \text{ GeV})^{-0.25} \text{ erg yr}^{-1} \) is the proton flux at the solar neighborhood (e.g. Naab & Ostriker 2006, and references therein), our galaxy.

The quoted production rate of our galaxy is estimated by (e.g. Berezinskii et al. 1990)

\[
\varepsilon_p^2 Q_{MW} \approx \varepsilon_p^2 \frac{dn}{d\varepsilon_p} M_{\text{gas}} / X_{\text{esc}} \approx 4 \times 10^{47} (\varepsilon_p/10 \text{ GeV})^{-0.25} \text{ erg yr}^{-1} \tag{8}
\]

where \( M_{\text{gas}} \sim 10^{10} M_\odot \) is the mass of the gas in the Galaxy (Naab & Ostriker 2006, and references therein),

\[
\frac{\varepsilon_p^2 dn}{d\varepsilon_p} \approx 0.12 (\varepsilon_p/10 \text{ GeV})^{-0.75} \text{ eV cm}^{-3} \tag{9}
\]

is the proton flux at the solar neighborhood (e.g. Moskalenko et al. 2002) and

\[
X_{\text{esc}} \approx 8.7 \left( \frac{\varepsilon_p/Z}{10 \text{ GeV}} \right)^{-0.5} \text{ g cm}^{-2}, \tag{10}
\]

is the average grammage traversed by the CRs which is deduced from the abundance of spallation secondaries (mainly from the ratio Boron/Carbon, e.g. Engelman et al. 1990; Jones et al. 2001; Webber 2003).

Equation (8) is insensitive to the poorly constrained values of the CR confinement volume and confinement times. It can be derived directly using the following argument: The integrated grammage of all CRs (in an infinitesimal particle energy interval \( \varepsilon_p, \varepsilon + d\varepsilon_p \) over a long time \( T \) (longer than the escape time from the Galaxy) can be expressed in two ways: (i) The total amount of particles generated (within the particle energy interval), \( T Q_{MW} \) times the average grammage each traversed \( X_{\text{esc}} \).

(ii) The instantaneous total rate of grammage being traversed, \( dn M_{\text{gas}} c T \), times the total time \( T \), where \( dn \) is the density of CRs within the particle energy interval. By equating these expressions, \( T Q_{MW} X_{\text{esc}} = dn M_{\text{gas}} c T \), Eq. (8) is obtained (by dividing by \( d\varepsilon_p \)). It is assumed however that the flux of CRs is roughly uniform throughout the galactic disk and that the average grammage is similar to that in the solar neighborhood. If CRs cannot propagate freely across the Galaxy, this estimate may have a large error. However, in this latter case, a local estimate would be more accurate and yields approximately the same value. Assuming a local gas surface density of \( 10 M_\odot \text{pc}^{-2} \) and local SFR of \( 2 M_\odot \text{pc}^{-2} \text{Gyr}^{-1} \) (e.g. Kennicutt & Evans 2012), would result in the same generation rate per SFR as implied by Eq. (7).

If, as currently widely believed, CRs originate from SNe, Eq. (7) would require an energy per supernova (per log particle energy) of \( \varepsilon_p^2 Q / n_{SN} \sim 2 \times 10^{45} \text{ erg} \) where \( n_{SN} \sim 10^{-4} \text{ Mpc}^{-3} \) is the rate of supernovae at \( z = 0 \) (Horiuchi et al. 2009).

The fact that the CR production estimate based on the Milky Way and that based on star-burst galaxies deviate by \( \sim 5 \) should not be surprising given the large uncertainties in each of these estimates. In particular the star-formation estimates are uncertain by a factor of at least 2. We conclude that the current rate of CR production is of order \( 10^{46} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \).

2.4. Comparison with earlier work

In Parizot 2005; Aublin & et al. 2005., the production rate of CRs was estimated to be 1000 times higher than that of UHECRs using the same basic assumption that other galaxies have acceleration efficiencies which are similar to ours. This ratio is much higher than the ratio of \( \sim 10 \) we estimated above. After carefully comparing our analysis we found that the main difference is due to the fact that Parizot (2005); Aublin & et al. 2005. ignored the interactions of the UHECRs with the CMB and therefore underestimated their production rate. For example, in Aublin & et al. 2005., the effective life time of UHECRs was estimated to be \( 25 H^{-1}_0 e^{-0.85} \sim 6 \times 10^{20} \text{ yr} \) which is about 20 times longer than the actual time they can propagate before losing a significant amount of energy due to the interaction with the CMB and adiabatic losses [see Eq. (2)]. In addition, the halo size and escape time adopted by these authors for estimating the galactic CR production rate is not compatible with the measured grammage (a factor of \( \sim 4 \) discrepancy). This last inaccuracy was partially canceled by their use of an effective galaxy density of \( n_{gal} \sim 3 \times 10^{-3} \text{ Mpc}^{-3} \) rather than our scaling by SFR which is equivalent to an effective galaxy density of \( \text{SFR}(z = 0)/\text{SFR(MW)} \sim 7.5 \times 10^{-3} \text{ Mpc}^{-3} \).

3. DISCUSSION

In this letter we showed that the production of low energy CRs (\( \varepsilon_p \sim 10^{40} \text{ eV} \)) in the local universe is \( \varepsilon_p^2 Q \sim 10^{45} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \) (Eqs. (5) and (7), with a large uncertainty) and is not much higher (\( \sim 10 \) times higher) than the lower limit for production of extra-galactic CRs with intermediate energies (\( \varepsilon_p \sim 10^{17} \text{ eV} \)) and ultra-high energies (\( \varepsilon_p \gtrsim 10^{19.5} \text{ eV} \)). It is thus possible that all CRs are generated in galaxies like our own with an energy production efficiency which is very slowly declining across the 10 orders of magnitude of CR energies (see figure 1).

The similarity between the energy production rates of CRs throughout the particle energy range \( 10^{16} \text{eV} \) to \( 10^{19} \text{eV} \), is consistent with a universal CR energy production rate in galaxies with a CR spectrum of \( \varepsilon_p \sim 10^{17} \text{ eV} \) and few power-law slopes is expected for astrophysical sources which accelerate particles in strong collisionless shocks, including non relativistic (e.g. Krymskii 1977; Bell 1978; Blandford & Ostriker 1978) and relativistic (e.g. Kirk & Schneider 1987; Bednaj & Ostrowski 1998; Achterberg et al. 2001; Keshet & Waxman 2003; Keshet 2006; Katz et al. 2007; Spitkovsky 2008) shocks, and is found in supernovae (e.g. Reynolds & Ellison 1992) and \( \gamma \)-ray bursts (e.g. Waxman 1997).

If CRs are produced with the suggested spectrum in galaxies like our own, including our own, the generation spectrum at high energy, \( \varepsilon_p \gtrsim 10^{17} \text{ eV} \), within our galaxy should be

\[
\varepsilon_p^2 Q_{MW} \sim 10^{46} \text{ erg yr}^{-1} \tag{11}
\]

and would imply an averaged local energy density of at least \( \varepsilon_p^2 n \gtrsim \varepsilon_p^2 Q_{MW} / (A_{MW} c) \sim 2 \times 10^{-17} \text{ eV cm}^{-3} \), where \( A_{MW} \sim 1000 \text{ kpc}^2 \) is the area of the Galaxy. This energy density is much higher than the observed energy density above the knee. This apparent discrepancy can be reconciled only if the sources are transient (Loeb & Waxman 2002), and the flux we are currently observing is low compared to the averaged flux.
While the (very rough) apparent similarity of production rates at low, intermediate and ultra-high energies may well be a coincidence, the most exciting possibility is that there is one type of such transient sources that emits the CRs at all observed energies (Parizot 2005, Aublin & et al 2005). In this case, the rate of occurrence of these sources and their energy output is constrained by the observed CR spectrum. Their energy output should explain that of the Milky Way implying $N_{MW}\dot{E}_{CR} \sim 10^{48}$ erg yr$^{-1}$ [see Eq. (8)], while their rate should be lower than the CR confinement region’s light crossing time to allow the dim state observed at the energies above the knee (Loeb & Waxman 2002). The scale height of the CR confinement region at very high energies is unknown and can be anywhere between the disk scale height $\sim 300$pc and the size of the Galaxy $\sim 10$kpc. These two limits imply very different (maximal) event rates of $(1000\text{yr})^{-1}$ and $(3\times10^3\text{yr})^{-1}$ in the local 300pc region or the entire galaxy respectively. These rates imply in turn a wide range of allowable values for the CR energy release per event of $E_{CR} \gtrsim 10^{47}$ erg and $E_{CR} \gtrsim 3 \times 10^{52}$ erg. The range of allowable energy outputs may be reduced by reducing the uncertainty in the CR disk scale height.

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