AN ESTIMATION OF THE POSSIBLE FLUX OF GALACTIC STRANGELETS IN THE SOLAR NEIGHBORHOOD

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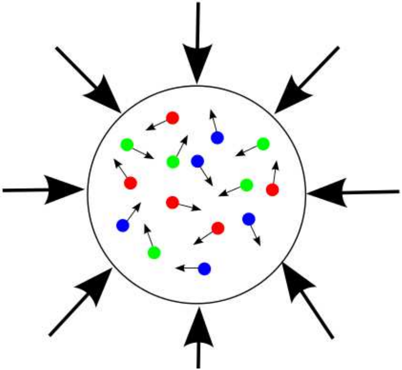
Outline

- About Strange Quark Matter (SQM), bag model and strangelet.
- Possible sources of strangelets.
- Statistical Multifragmentation Model (SMM).
- Implementation of SMM in SQM system.
- Derived mass-spectrum for strangelets.
- Estimation of flux of strangelets in the solar neighborhood.

About Strange Quark Matter (SQM)

- SQM : Large, but roughly equal numbers of u, d and s quarks enclosed in a bag.
- Bag is physically realized by a pressure B exerted from the surrounding vacuum on the quark-system. It simulates confinement of the quark-collection.



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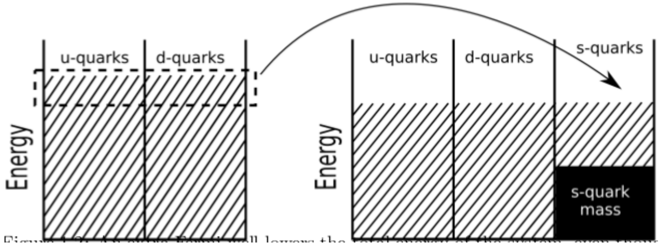
- SQM (with appropriate bag parameters) may be the true ground state of hadronic matter (E. Witten, PRD 30 (1984) 272).



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- Strangelets : Small ($A < 10^7$) 'nuggets' of SQM may also be stable (compared to normal nuclei) despite finite size (surface and curvature) effects (E. Farhi and R.L. Jaffe, PRD 30 (1984) 2379).

- Bag values are in the range (J. Madsen, Lecture Notes in Physics, Springer Vol. No. 516, 1999, p. 162):

$$145\ \mathrm{MeV} \lesssim B^{1/4} \lesssim 163\ \mathrm{MeV}.$$

Strangelets in cosmic rays??

- Ongoing efforts by CAPSS, Bose Institute to search for anomalous events including strangelet in atmospheric cosmic rays at high altitude (Darjeeling, Hanle, Sandakfu). Theoretical works have been done on propagation of strangelet in the atmosphere (S. Banerjee *et al.* J. Phys. G 25 (1999) 15, S. Banerjee *et al.* PRL 85 (2000) 1384).

- AMS-01 found an anomalous event (Z = 2, Z/A $\sim$ 0.1). Estimated intensity $\sim 1.5x10^3$ particles $\mathrm{m}^{-2}\ \mathrm{sr}^{-1}\mathrm{yr}^{-1}$ (A. Kounine, XVI ISVHECRI (2010), Batavia, IL, USA).

- Ongoing AMS-02 (on-board ISS) experiment to detect strangelets of Z $\lesssim$ 30, A $\lesssim 10^3$; sensitivity $\sim$ 1 particles $\mathrm{m}^{-2}\ \mathrm{sr}^{-1}\mathrm{yr}^{-1}$ (A. Kounine, XVI ISVHECRI (2010), Batavia, IL, USA).

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- Recently PAMELA reported null results for $Z = 1, 2......8$ candidates and set a new upper limit of flux for strangelets at the TOA (O. Adriani *et al.* (PAMELA collaboration) PRL 115 (2015) 111101.
- Recent Simulations : Population averaged ejected mass of ordinary SQM ($B^{1/4} = 145$ MeV) is $\sim 10^{-4} M_{\odot}$ per SS merger in compact binary stellar systems (A. Bauswein *et al.* PRL 103 (2009) 011101; A. Bauswein *et al.* PRD 81 (2010) 024012).

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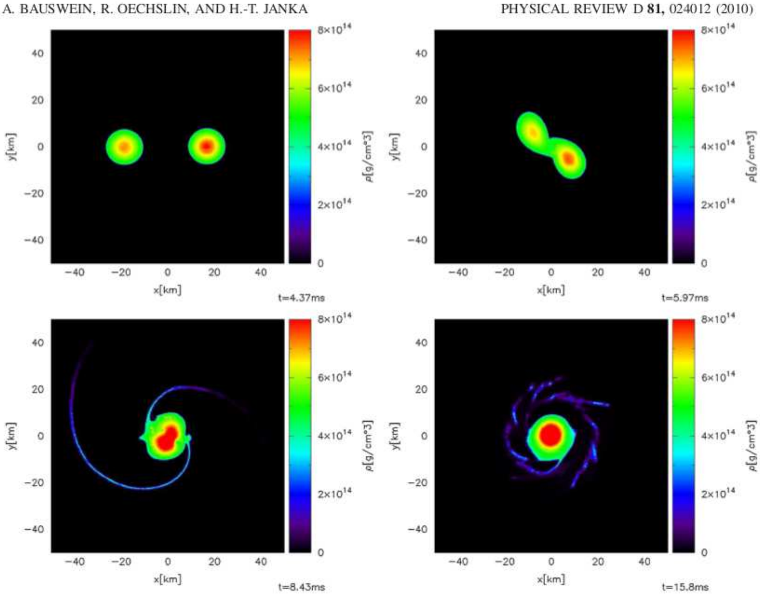

A. BAUSWEIN, R. OECHSLIN, AND H.-T. JANKA
PHYSICAL REVIEW D 81, 024012 (2010)
y[km]
x[km]
ρ[g/cm^3]
8×10^14
6×10^14
4×10^14
2×10^14
0
t=4.37ms
t=5.97ms
t=8.43ms
t=15.8ms

- Recent observations and theoretical calculations predict a Galactic binary merger rate of about $10^{-7} - 10^{-4}\ \mathrm{yr}^{-1}$(K. Belczynski *et al.* Astrophys. J. Lett. 680 (2008) L129).
- Ejected Strange-matter is likely to fragment into strangelets of possible sizes $A \approx 10^2 - 10^4$ that contribute to primary cosmic rays (PRM-CR) (J. Madsen PRD 71 (2005) 014026).
- J. Madsen (2005) developed propagation model in the Galaxy by assuming SQM-nuggets of equal size.
- Important is to find realistic size-distribution (i.e., fragmentation pattern) of strangelets (J. Madsen, 2005; S. Biswas *et al.* PLB 715 (2012) 30).

Analogy from Nuclear Fragmentation (J.P. Bondorf *et al.* Phys. Rep. 257 (1995) 133)

- Warm and excited nuclear matter evolves in thermodynamic equilibrium through expansion.
- Undergoes disassembly after reaching a freeze-out volume at temperature T.
- Strong interactions between fragments cease to be important at freeze-out.

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- The multiplicity of a fragment of species i is given as(J.P. Bondorf *et al., 1995, S. Biswas et al., 2012*),

$$\omega^i = \frac{\mathcal{V}}{(\mathcal{L}^i)^3} e^{(\mu^i - F^i)/T}. \tag{1}$$

★ $\mathcal{V}$ = Available volume (Freeze-out volume minus the volume occupied by the fragments) (A.S. Botvina and I.N. Mishustin, Eur. Phys. J. A 30 (2006) 121).

★ $\mathcal{L}^i = h/\sqrt{2\pi m^i T}$ is the thermal de-Broglie wavelength, h is the Planck's constant and T is the temperature at freeze-out.

★ m^i = mass of the fragment of i^{th} species (J. Madsen, Lecture Notes in Physics 516 (1999) 162).

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- $\mu^i = \sum_f \mu_f N_f^i$ is the chemical potential of the $i^{\rm th}$ species. The quark chemical potential is μ_f with 'f' indicating a particular quark-flavor (i.e. $f = u, d, s$). Also, $N_f^i = \left(-\frac{\partial \Omega_f^i}{\partial \mu_f}\right)_{V^i, T}$ is the number of quarks of the $f^{\rm th}$ flavor in the $i^{\rm th}$ specie of volume V^i, their thermodynamic potential is Ω_f^i.
- $F^i = \Omega^i + \mu^i + E_{\rm C}^i$ stands for the Helmholtz free energy of the $i^{\rm th}$ species while $E_{\rm C}^i$ is its Coulomb energy. F^i may be rewritten as $F^i = {\Omega^i}_{\rm tot} + \mu^i$, where, $\Omega_{\rm tot}^i = \Omega^i + E_{\rm C}^i$.

Now, Eq.(1) can be written as

$$\omega^i = \frac{\mathcal{V}}{(\mathcal{L}^i)^3} e^{-\Omega_{\rm tot}^i / T}. \qquad (2)$$

Simplifying assumptions and parameter choices

- $m_u = m_d = 0$ & $m_s = 95$ MeV(J. Beringer *et al.* (PDG) PRD 86 (2012) 010001, http://pdg.lbl.gov/2013/tables/contents_tables.html).
- $\mu_f = \mu_q - Q_f\mu_e$, where, $\mu_e = \frac{m_s^2}{4\mu_q}$ (M. Alford and K. Rajagopal JHEP 06 (2002) 31).
- Spherical strangelets with a radius parameter r_o^i:
  Volume : $V_i = 4\pi(r_\text{o}^i)^3 A_i/3$,
  Surface : $S_i = 4\pi(r_\text{o}^i)^2 A_i^{2/3}$,
  Curvature : $C_i = 8\pi(r_\text{o}^i) A_i^{1/3}$.

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- Temperature of the accretion disk of the compact X-ray binary system $\sim$ 1 keV (S. Rosswog, M. Bruggen, *Introduction to High-Energy Astrophysics, Cambridge, England, 2007*).
- Temperature of cold/low entropy material ejected from the tidal arms formed during simulations of NS merger is $\sim$ 1 MeV (R. Oechslin *et al.* Astron. Astrophys. 467 (2007) 395).
- We consider temperatures in the range 1 keV $\lesssim T \lesssim$ 1 MeV at freeze-out for the initial SQM ejected during SS-mergers.
- For the baryon number of the initial SQM, we consider $A_b = 1 \times 10^{53}$ that is consistent with the simulations (A. Bauswein *et al.* 2009, 2010).

Properties of a strangelet. Volume contribution

Thermodynamic potential of the $i^{\rm th}$ species is written as

$$\Omega^i = \Omega^{\rm o}_{\rm V} {\rm V}^i + \Omega^{\rm o}_{\rm S} {\rm S}^i + \Omega^{\rm o}_{\rm C} {\rm C}^i + B{\rm V}^i, \tag{3}$$

where (S. Biswas *et al.* (2015), arxiv:1409.8366, ICRC 2015, The Hague, The Netherlands. http ://pos.sissa.it/archive/conferences/236/504/ICRC2015 504.pdf.)

$$\begin{aligned}\Omega^{\rm o}_{\rm V} = & -\frac{37}{90}\pi^2 T^4 - \left(\frac{\mu_u^2+\mu_d^2}{2}\right) T^2 - \left(\frac{\mu_u^4+\mu_d^4}{4\pi^2}\right) \\ & -\frac{\mu_s^4}{4\pi^2}\left[\left(1-\frac{5}{2}\lambda_s^2\right)\sqrt{1-\lambda_s^2} + \frac{3}{2}\lambda_s^4 \ln\left(\frac{1+\sqrt{1-\lambda_s^2}}{\lambda_s}\right)\right. \\ & \left. +2\pi^2\left(\frac{T}{\mu_s}\right)^2\sqrt{1-\lambda_s^2} + \frac{7\pi^4}{15}\left(\frac{T}{\mu_s}\right)^4 \frac{(1-\frac{3}{2}\lambda_s^2)}{(1-\lambda_s^2)^{3/2}}\right],\end{aligned} \tag{4}$$

Surface contribution

$$\Omega_S^o = \frac{3}{4\pi}\mu_s^3\left[\frac{(1-\lambda_s^2)}{6} - \frac{\lambda_s^2}{3}(1-\lambda_s)\right.$$
$$-\frac{1}{3\pi}\left\{\tan^{-1}\left(\frac{\sqrt{1-\lambda_s^2}}{\lambda_s}\right) + \lambda_s^3 \ln\left(\frac{1+\sqrt{1-\lambda_s^2}}{\lambda_s}\right) - 2\lambda_s\sqrt{1-\lambda_s^2}\right\}$$
$$\left.+\frac{\pi}{3}\left(\frac{T}{\mu_s}\right)^2\left\{\frac{\pi}{2} - \tan^{-1}\left(\frac{\sqrt{1-\lambda_s^2}}{\lambda_s}\right)\right\} + \frac{7\pi^3}{180}\left(\frac{T}{\mu_s}\right)^4\frac{\lambda_s^3}{(1-\lambda_s^2)^{3/2}}\right] \quad (5)$$

Curvature contribution

and

$$\Omega_{\mathrm{C}}^{\mathrm{o}} = \frac{19}{36}T^2 + \left(\frac{\mu_u^2+\mu_d^2}{8\pi^2}\right)$$
$$+\frac{\mu_s^2}{8\pi^2}\left[\frac{1}{\lambda_s}\left\{\frac{\pi}{2}-\tan^{-1}\left(\frac{\sqrt{1-\lambda_s^2}}{\lambda_s}\right)\right\}\right.$$
$$+\left(\frac{\pi^2}{\lambda_s}\right)\left(\frac{T}{\mu_s}\right)^2\left\{\frac{\pi}{2}-\tan^{-1}\left(\frac{\sqrt{1-\lambda_s^2}}{\lambda_s}\right)\right\}$$
$$+\lambda_s^2\left\{\pi+\ln\left(\frac{1+\sqrt{1-\lambda_s^2}}{\lambda_s}\right)\right\}$$
$$\left.-\frac{3\pi}{2}\lambda_s-\left(\frac{2\pi^2}{3}\right)\left(\frac{T}{\mu_s}\right)^2\frac{1}{\sqrt{1-\lambda_s^2}}-\frac{7\pi^4}{60}\left(\frac{T}{\mu_s}\right)^4\frac{\lambda_s^2(1+\lambda_s^2)}{(1-\lambda_s^2)^{5/2}}\right]. \quad (6)$$

Here, $\lambda_s = \frac{m_s}{\mu_s}$.

- Charge of a fragment is (H. Heiselberg, 1993)

$$Z^i \approx \frac{m_s^2}{4\alpha\mu_q} R^i \left[1 - \frac{\tanh(R^i/\lambda_D)}{(R^i/\lambda_D)}\right] \tag{7}$$

and Coulomb energy is (H. Heiselberg, 1993)

$$E_C^i \approx \frac{m_s^4}{32\alpha\mu_q^2} R^i \left[1 - \frac{3}{2}\frac{\tanh(R^i/\lambda_D)}{(R^i/\lambda_D)} + \frac{1}{2}\left\{\cosh(R^i/\lambda_D)\right\}^{-2}\right]. \tag{8}$$

Energy and mechanical equilibrium

- The entropy of the strangelet of the $i^{\rm th}$ species is $\mathcal{S}^i = -(\frac{\partial \Omega^i}{\partial T})_{\mathrm{V}^i, \mu^i}$. Thus, the total energy of the strangelet may be written as

$$\begin{aligned} E^i = & \quad T\mathcal{S}^i + \mu^i + \Omega^i_{\rm tot} \\ = & \quad T\mathcal{S}^i + \mu^i + \Omega^i + E^i_{\rm C}. \end{aligned} \quad (9)$$

- Under mechanical equilibrium, $P^i_{\rm ext} = -(\frac{\partial \Omega^i_{\rm tot}}{\partial \mathrm{V}^i})_{T, \mu^i}$, where, $P^i_{\rm ext}$ is the external pressure on a strangelet of the $i^{\rm th}$ species

Wigner-Seitz (WS) approximation

- $V^i_{\rm cell} = \frac{Z^i}{\sum_i Z^i \omega^i}\mathcal{V}$ satisfies the constraint $\sum_i \omega^i V^i_{\rm cell} = \mathcal{V}$.
- $n^i_{\rm e} = Z^i / V^i_{\rm cell} = n_e = \frac{\mu^3}{3\pi^2}$.
- The expression for the external pressure of highly relativistic electrons on the strangelet may then be written as (E.E Salpeter ApJ 134 (1961) 669)

$$
\begin{aligned}
P^i_{\rm ext} &= (3\pi^2)^{1/3}\left[\frac{(n^i_{\rm e})^{4/3}}{4}\right] + \left(\frac{\pi^2}{6}\right)\left[\frac{T^2}{(3\pi^2)^{1/3}}\right](n^i_{\rm e})^{2/3} \\
&-\left(\frac{3}{10}\right)\left(\frac{4\pi}{3}\right)^{1/3}\alpha (Z^i)^{2/3}(n^i_e)^{4/3} \\
&-\left(\frac{1}{6}\right)\left(\frac{324}{175}\right)\left(\frac{4}{9\pi}\right)^{2/3}(3\pi^2)^{1/3}(Z^i)^{4/3}\alpha^2(n^i_e)^{4/3} \\
&+\left(\frac{1}{8\pi}\right)\alpha(3\pi^2)^{1/3}{n^i_e}^{4/3} - \frac{0.062}{6}\alpha^2 m_e n^i_e \qquad (10)
\end{aligned}
$$

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- $$\Omega^i_{\rm tot} = (-\Omega^{\rm o}_{\rm V} - B)\mathrm{V}^i\left(\frac{\Omega^{\rm o}_{\rm S}\mathrm{S}^i + 2\Omega^{\rm o}_{\rm C}\mathrm{C}^i + 3E^i_{\rm C} - \Delta E^i_C - 3P^i_{\rm ext}\mathrm{V}^i}{2\Omega^{\rm o}_{\rm S}\mathrm{S}^i + \Omega^{\rm o}_{\rm C}\mathrm{C}^i + \Delta E^i_C + 3P^i_{\rm ext}\mathrm{V}^i}\right), \tag{11}$$

  where,

  $$\Delta E^i_C \approx \frac{(\Delta\mu_q)^2}{2\alpha}R^i\left[1 - \cosh^{-2}\left(\frac{R^i}{\lambda_D}\right)\left\{1 + \left(\frac{R^i}{\lambda_D}\right)\tanh\left(\frac{R^i}{\lambda_D}\right)\right\}\right]. \tag{12}$$

Baryon number conservation

- No. of u-quarks in i^{th} fragment is

$$N_u^i = A^i + Z^i. \tag{13}$$

- Global charge-neutrality is given by (S. Biswas *et al.* 2015)

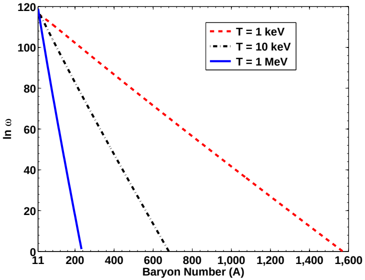
$$\sum_i \frac{\omega^i}{\mathcal{V}} Z^i = \sum_i n^i Z^i = n_e = \frac{m_s^6}{192\pi^2\mu_q^3} \tag{14}$$

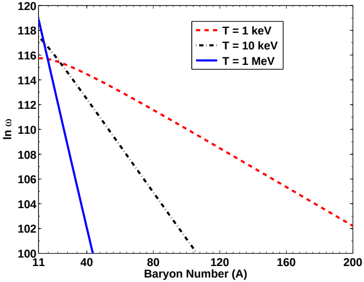
- Conservation equation (S. Biswas *et al.*, 2012, 2015)

$$\mathcal{V} = \frac{A_b}{\sum_i A^i n^i}. \tag{15}$$

is solved along with other eqs. to obtain the multiplicities of fragments.

Derived mass spectrum





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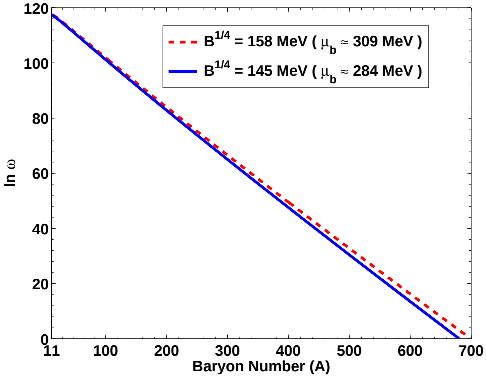
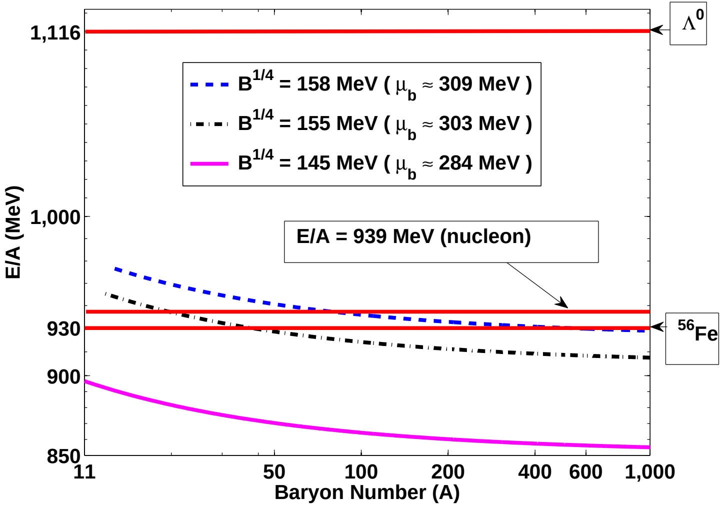


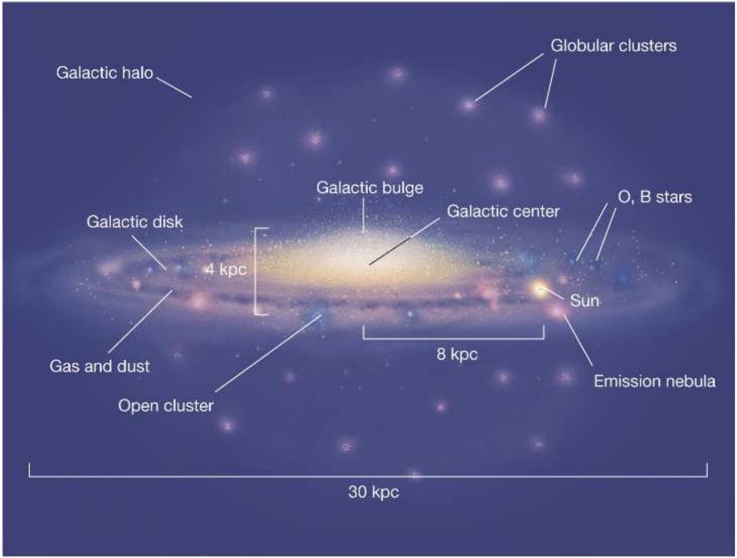
$B^{1/4}$ = 158 MeV ($\mu_b \approx$ 309 MeV)
$B^{1/4}$ = 145 MeV ($\mu_b \approx$ 284 MeV)
ln ω
Baryon Number (A)
120
100
80
60
40
20
0
11
100
200
300
400
500
600
700

Continued...



1,116
1,000
930
900
850
E/A (MeV)
Λ^0
B^1/4 = 158 MeV (μb ≈ 309 MeV)
B^1/4 = 155 MeV (μb ≈ 303 MeV)
B^1/4 = 145 MeV (μb ≈ 284 MeV)
E/A = 939 MeV (nucleon)
^{56}Fe
11
50
100
200
400
600
1,000
Baryon Number (A)

Structure of our Galaxy



- Being charged particles, the strangelet-fragments, after originating from the SS merger event, are expected to undergo Fermi acceleration by interacting with shock wave produced from the SS collision.

- The resultant energy spectrum of all the strangelets, summed over their species, is expected to be a power law $dN/d\mathcal{E} = \mathcal{N}_o\mathcal{E}^{-\alpha}$. Here, $N(\mathcal{E})d\mathcal{E}$ is the (assumed) number of strangelets with their kinetic energy being in the range $[\mathcal{E}, \mathcal{E} + d\mathcal{E}]$ with $\mathcal{N}_o$ being a normalization constant. The spectral index is assumed to have a value around $\alpha \approx 2.2$ (Madsen 2005).

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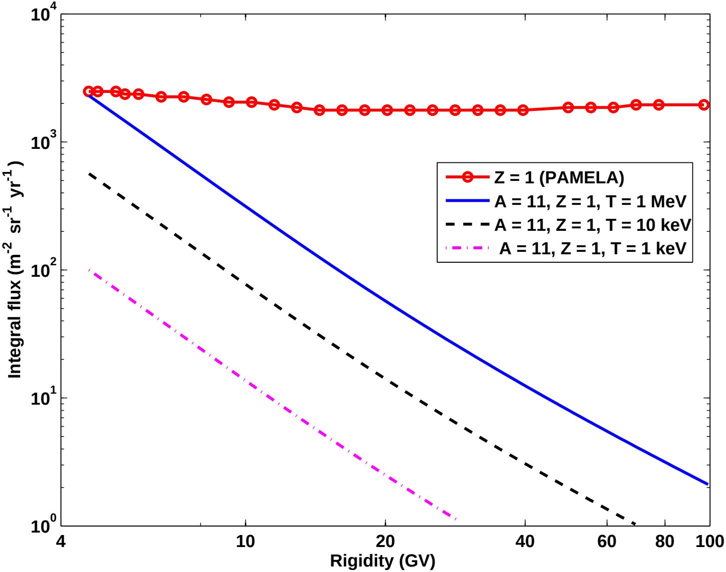
- Strangelets obey a steady state distribution and for the sake of simplicity we consider sources are distributed uniformly over the galactic disc.
- If the shock energy is $\sim 10^{49}$ ergs then the integral flux of the $i^{\rm th}$ species (of stable strangelets) is given as

$$I^i(\mathcal{R}^i) = 2.1 \times 10^3 \frac{\omega^i}{\sum_i \epsilon^i_{min}\omega^i}(Z^i)^{1.5} \int_{\mathcal{R}^i_{min}}^{\mathcal{R}^i_{max}} (\beta^i)^2(\eta^i)^{-2.7} d\mathcal{R}^i \ \mathrm{m^{-2}sr^{-1}yr^{-1}} \quad (16)$$

Continued...

- $\epsilon^i_{min} = \frac{1}{2} m^i_0 \beta^2_{min}$ with $\beta_{min} = v^i_{min}/c = 0.15$ and $\eta^i = (\frac{\mathcal{R}^i Z^i}{\beta^i} - m^i_0)$.
- SS merger rate $10^{-7}\mathrm{yr}^{-1}$ and the energy dependent diffusion coefficient $D^i = 3 \times 10^{28} \left(\frac{\mathcal{E}^i}{1\mathrm{GV}\ Z^i} \right)^{0.5} \mathrm{cm}^2/\mathrm{s}$.

Comparison with PAMELA results



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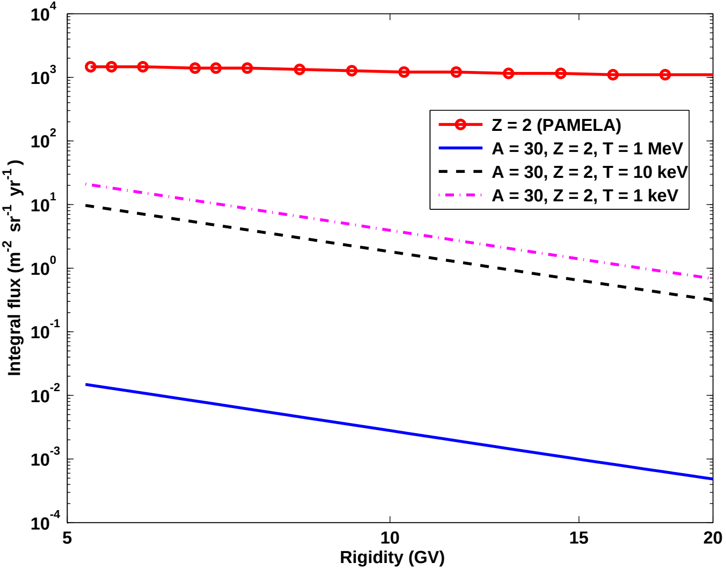
Integral flux (m^{-2} sr^{-1} yr^{-1})
Rigidity (GV)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
5
10
15
20
Z = 2 (PAMELA)
A = 30, Z = 2, T = 1 MeV
A = 30, Z = 2, T = 10 keV
A = 30, Z = 2, T = 1 keV

THANK YOU