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The Origin of the Most Energetic Galactic Cosmic Rays: Supernova Explosions into Massive Star Plasma Winds

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Abstract: We propose that the high energy Cosmic Ray particles around the spectral turn-down commonly called the *knee* and up to the upturn, commonly called the *ankle*, mostly come from Blue Super Giant star explosions. At the upturn, i.e. the *ankle*, Cosmic Rays probably switch to another source class, most likely extragalactic sources. To show this we recently compiled a set of Radio Supernova data to list the magnetic field, shock speed and radius scale (Biermann et al. 2018) [43]. Using particle acceleration theory at shocks, those numbers can be transformed into characteristic *knee* and *ankle* energies. Without adjusting any free parameters both of these observed energies are directly indicated by the supernova data. We now proceed to the next step in the argument, and use the Supernova Remnant data of the starburst galaxy M82. Assuming that they are Blue Supergiant star explosions, the shock will race to their outer edge with a magnetic field that follows $B(r)r \sim const.$. We argue that the shock runs through the entire magnetic plasma wind region at full speed all the way out to the wind-shell, which is of order parsec scale. The speed is observed to be $\sim 0.1c$ at about 10^{16} cm radius in the plasma wind. This demonstrates how Blue Supergiant star explosions can provide the Cosmic Ray particles across the *knee* and up to the *ankle* energy range. The data from the CREAM (Cosmic Ray Energetics and Mass Experiment) mission will test this cosmic ray concept which is reasonably well grounded in two independent radio supernova data sets. The next step in developing our understanding is to obtain accurate Cosmic Ray data near to the *knee*, and use unstable isotopes of Cosmic Ray nuclei at high energy to probe the "piston" driving the explosion. We plan to combine these data with the physics of the budding black hole which is probably forming in each of these stars to learn more.

Keywords: Cosmic Rays; Massive Star Supernovae; Cosmic Ray Knee and Ankle.

1. Introduction

Energetic particles with energies far above thermal levels, called cosmic rays, were discovered by Hess (1912) [78] and Kohlhörster (1913) [86], with their energies now known to range up to about 10^{20} eV, first seen by Linsley (1963) [100]. It was proposed very early (Baade & Zwicky 1934) [29] that supernovae could easily provide the energies required for Galactic cosmic rays (GCRs). Ginzburg & Syrovatskij (1963) [71] suggested that radio galaxies could provide the highest energy component.

The mechanism of acceleration was originally proposed by Fermi (1949, 1954) as repeated reflections between interstellar clouds with magnetic field bottle configurations which are approaching each other. This was later generalized to today's concept of energetic particles being reflected back and forth across a shock wave, separating converging flows (Axford et al. 1977; Krymskii 1977; Bell 1978a,b; Blandford & Ostriker 1978; [28,32,33,46,95]), with early general overviews by Ginzburg & Ptuskin (1976) [72] and Drury (1983) [62]. It is now recognized that such particles permeate interstellar space, as well as intergalactic space. Particle energies above order GeV are found throughout the Solar system. The early arguments on their possible origin were all made on the grounds of sufficient energy supply, and they still stand. However we now know of many other processes and events of stars and black holes that clearly produce energetic particles.

In addition to the *supernova* origin of accelerated CRs and outflow (the theme of this paper), is energy outflow and particle acceleration due to central supermassive black holes, and their jets and lobes. Cosmic rays, magnetic fields and energy from SMBH-powered jets are additional phenomena to SN-generated CRs. They have been discussed by e.g., Ginzburg & Syrovatskij (1963) [71], Lovelace (1976) [101], Biermann & Strittmatter (1987) [35], Kronberg et al. (2001) [92], Kronberg (2002) [93], Colgate (2004) [56], Colgate et al. (2014) [57], Biermann et al. (2016) [42], and in many other papers.

Some recent relevant reviews and books are Aharonian (2004) [19], Stanev (2010) [133], Kotera & Olinto (2011) [87], Letessier-Selvon & Stanev (2011) [99], Bykov et al. (2012) [49], Diehl (2013, 2017) [60,61], Blasi (2013) [47], Gaisser et al. (2016) [68], Kronberg (2016) [94], Amato & Blasi (2017) [27], and Biermann et al. (2018) [43], referred to as ASR18. Many further tests can now be done with new results from Auger, the Telescope Array, IceCube, AMS, HAWC, HESS, MAGIC, CALET, DAMPE, and Veritas, further balloon flights, such as TIGER, and other experiments in space, on balloons, and on the ground. ISS-CREAM is the next major space experiment with new data yet to come, following on AMS (Seo et al. 2014, Seo 2018, [126,127]).

2. Massive star plasma winds

Massive stars explode as Supernovae (SNe). The shock pushed out by the explosion can accelerate cosmic ray (CR) particles. When this shock races through a stellar magnetic plasma wind, particle energies can go as high a few 10^{18} eV (Stanev et al. 1993, referred to as CR-IV, [132]). Massive stars with magnetized plasma winds come in two varieties, Red Supergiant (RSG) stars above about $25 M_{\odot}$ Zero Age Main Sequence (ZAMS) mass, and Blue Supergiant (BSG) stars, above about $33 M_{\odot}$ ZAMS mass. All of these are in binary systems, but not all of them are in tight orbits. RSG star magnetic plasma winds have a low velocity and high density whereas BSG star magnetic plasma winds have a very high velocity and low density. In the time period preceding the SN explosion, this plasma wind experiences short episodes during which the star may enhance its mass loss, and magnetic fields (as summarized with many references, e.g., in ASR18 [43]). The plasma wind terminates in a shell, where it encounters the interstellar medium (ISM), the molecular cloud (MC), out of which the star formed, and/or the wind-bubble environment of preceding SN explosions in its immediate environment. As the ram pressure of RSG star plasma winds is two orders of magnitude lower than for BSG star plasma winds, the wind shell may have a radial scale about an order of magnitude smaller than BSG star plasma winds. It also follows that the life-time of activity for RSG star explosions is an order of magnitude shorter than for BSG star explosions. This provides a strong counter selection effect in identifying such sources. When the SN shock does hit the wind shell, it slows down considerably; for radio supernovae (RSNe) the SN-shock speed is typically $0.1 c$, while for the Super Nova Remnants (SNRs) in M82 (Kronberg et al. 1985, hereafter referred to as KBS85, [90]) the observed velocities of expansion (e.g. Fenech et al. 2008, 2010, [63,64]) are all far below this value; this observation matches the expectation that upon encountering the wind shell the SN plasma shock reverts to environment-dominated expansion (e.g. Cox 1972). That reversion causes the shocked region to be about $1/4$ of the spherical volume encompassed by the shock, rather than $3/4$ as in the shocked region in a wind (Biermann & Cassinelli 1993, [38], Biermann & Strom 1993, [39], referred to as CR-II and CR-III; this uses a strong shock, see

Landau & Lifshitz 1959, [98], and Drury 1983, [62]). When a SN shock races through a stellar plasma wind, it produces radio emission that can be detected with interferometry (i.e. sub-arcsecond radio imaging) to determine the magnetic field $B(r)$, the mass loss \dot{M}_* , its radial scale r , and velocity V_{SN}/c . We note that V_{SN} is the velocity of the shock in the medium, through which it propagates, here the wind of the star. As these shocks are observed to show about $0.1 c$, we can neglect the prior velocity of the wind. From these three quantities, scale r , magnetic field B , and shock speed V_{SN}/c we can derive two critical energies for the maximal energies particles can reach in shock acceleration, E_{knee} and E_{ankle} , first the maximal energy of a particle fitting into the space available (for a plasma simulation see Meli & Biermann 2006, [105], and for an analytical derivation see, e.g., Biermann 1993, referred to as CR-I, [37], or ASR18 [43]),

$$E_{ankle} = \frac{1}{8} Z e B_0 r_0, \quad (1)$$

where e is the elementary charge, Z is the charge of the particle under consideration (cgs units). We have used here the Parker (1958) [121] plasma wind property that

$$B_\phi(r) \times r = B_0 r_0 \sim const. \quad (2)$$

consistent with the observations discussed here; here B_ϕ is the dominant component of the magnetic field (Parker 1958, Weber & Davis 1967 [121,142]). We interpret the associated energy as the *ankle* in the spectrum of Galactic CRs (GCRs). This corresponds to energies reached in perpendicular shocks (see Jokipii 1987, [82], Völk & Biermann 1988, [138], CR-I, CR-IV, Meli & Biermann 2006, [37,105,132], and ASR18 [43]). A lower break energy corresponds to the *knee*, where the spectrum turns down:

$$E_{knee} = \frac{1}{8} Z e B_0 r_0 \left(\frac{V_{SN}}{c} \right)^2. \quad (3)$$

For the observed numbers of RSNs (ASR18 [43]) the energies derived match the energies for *knee* and *ankle* directly, to within the errors, without using any parameter adjustment. We note that to obtain these numbers we take the observed data and average the products $\langle r \times B(r) \rangle$ and $\langle r \times B(r) \times (V_{SN}/c)^2 \rangle$. The numbers show that the ratio of these two averages is $10^{-1.6}$ between them, instead of 10^{-2} , as would be expected by multiplying separate averages, suggesting the possibility that these numbers might be weakly correlated.

However, as these observations show the situation typically around $r \simeq 10^{16}$ cm, due to opacity effects, we need to ascertain what happens at the larger scale, when the SN-shock actually hits the wind shell or other environment. This is possible with the data from M82:

We propose to test this concept with the observations of the SNRs in M82 (KBS85 [90]; Bartel et al. 1987, [30]; Muxlow et al. 1994, [117]; Golla et al. 1996, [73]; Allen & Kronberg 1998, [26]; Allen 1999, [25]; Kronberg et al. 2000, [91]; McDonald et al. 2002, [104]; Muxlow et al. 2005, [118]; Fenech et al. 2008, 2010, [63,64]; Gendre et al. 2013, [69]).

3. The Super Nova Remnants in the starburst galaxy M82

Here we show the data on all supernova remnants (SNRs) in M82 that have published derived estimated magnetic fields and for which the size was clearly established (Allen & Kronberg 1998, Allen 1999, [25,26] with many further references therein):

The flux density values listed in Table 1 for the non-thermal emission are referenced to a frequency of 1 GHz, and were obtained by a fit across very many frequencies, from 408 MHz all the way to 23.46 GHz, using a screen model absorption and separating thermal from non-thermal emission. The spectral index given is that of the non-thermal straight power-law component. The magnetic field derived in Allen & Kronberg (1998) [26] has to be scaled with the factor $\{(1+k)/\phi\}^{2/7}$, which is highly uncertain; here k is the ratio of the CR proton energy density to that of CR electrons, at an energy of a few GeV - at lower particle energy this ratio is expected to be smaller, since protons do not

Table 1. Supernova remnants (SNRs) in starburst galaxy M82, based on Allen & Kronberg (their Table 5; 1998) [26], in turn based on Allen (1999) [25]

Coordinate name	size $2r$ in pc	flux density in mJy	sp. index	est. magnetic field B in mGauss	$\log(Br)$ in Gauss \times cm
40.68 + 550	3.72	17.9	-0.52	1.80	16.0
41.31 + 596	2.17	8.59	-0.54	2.32	15.9
41.96 + 574	0.33	122.8	-0.72	26.4	16.1
42.53 + 619	1.71	30.9	-1.84	11.7	16.5
42.67 + 556	3.02	4.44	-0.61	1.46	15.8
43.19 + 583	1.16	15.3	-0.67	4.79	15.9
43.31 + 591	3.02	30.3	-0.64	2.54	16.1
44.01 + 595	0.78	62.0	-0.51	9.83	16.1
44.52 + 581	3.72	7.2	-0.61	1.40	15.9
45.18 + 612	3.49	24.1	-0.68	2.13	16.1
45.86 + 640	1.09	4.10	-0.53	3.39	15.8
46.52 + 638	3.88	9.71	-0.73	1.53	16.0
46.70 + 670	3.4119	5.22	-0.57	1.37	15.9

contribute any extra energy below their rest mass energy, but electrons continue to contribute due to their smaller rest mass. From above we adopt $\phi = 1/4$, since clearly the SN-shock has encountered the outer shell of the wind, and is observed to have slowed down. We list here the magnetic field without any such correction.

3.1. The CR proton/electron ratio k

For the CR proton/electron ratio k , observed to be about 100 above a few GeV, we can make the following argument, based on the observations of young RSNe (see ASR18 [43]): The first process that happens in an electron-proton shock is the thermalization of these particles. Thermalization has to work at all radii, from below 10^{16} cm out to parsec scale, rendering the density lower by a factor of 10^5 at least. The wind is magnetic with the basic configuration of the magnetic field a Parker type spiral, so essentially yielding a perpendicular shock configuration. This process has been discussed in Spitzer (1962) [131], but his treatment is non-relativistic and uses isotropic phase space distributions; then simple electron-proton scattering is far too slow at high temperature. When the protons go through the shock, they fill in phase space a torus with the radius in momentum $m_p V_{SN}$, and with the relative width of the inverse of the Mach-number, so corresponding to the upstream speed of sound. That entails that this anisotropic momentum distribution causes turbulence at all the scales from the maximum on down, over a range of the Mach-number. But because the Mach-number is close to m_p/m_e the smallest scales in this range correspond to the waves matching the scales of the electrons with the maximal momentum $m_e V_{SN}$. This means that at all these scales the protons and electrons are scattered in momentum phase space. We have argued in ASR18 [43] that the spectrum of irregularities in the direct shock region is $I(k)k \sim 1$ and so the power per log bin of wave-number is equal at all scales. It follows that thermalization occurs. Due to all this turbulence the time scale of thermalization is of order a small multiple of the thermal Larmor radius divided by the Alfvén speed, so highly adequate, by a factor of $2 E_{knee}/(m_p V_{SN}^2)$, and a fortiori $2 E_{ankle}/(m_p V_{SN}^2)$. The time scale for electrons might be m_p/m_e times slower due to the anisotropy of the scattering, but that is still quite adequate by many powers of ten. This time scale scales with the radius, and so works the same at all relevant radii, the condition noted above.

Thermalization yields a first characteristic energy of the electrons, $\gamma_{e,sh} c m_e$. Beyond this energy, our interpretation of the radio observations (ASR18 [43]) then says that the electrons gain energy only by drifts (CR-I [37]); shock acceleration does not work yet, because the electrons do not see the shock. In ASR18 [43] we noted that the electrons so only get stochastic shock drift acceleration, giving them a spectrum of -3.06, from observations, say about -3 (this line of reasoning was also used for ions by

Caprioli 2012 [51]). This drift dominated spectrum ranges to that momentum, at which the energetic electron reach a Larmor radius that equals that of the shock thermal protons, $\gamma_{sh,inj} c m_e$, (i.e., the electrons have the same Larmor radius as shock-protons; if another CR ion is dominant, corresponding to the Larmor radius of that ion, with mass number A_{dom} and charge at injection Z_{dom}). From this second momentum electrons "see" the shock, and have the normal CR accelerated spectrum, say $-7/3$ for the most common CR component of CRs accelerated in a wind (see ASR18 [43]). Protons attain the maximal energy content only at a few GeV (i.e. just above their rest mass energy). This applies to any particle number spectrum even slightly steeper than -2 . That implies that electrons have a higher energy content at that momentum, where they are still just above thermal in the post-shocked region. We assume that at this stage that electrons are in equipartition with the protons (or dominant ions), at the start due to charge neutrality.

This means that

$$\gamma_{e,sh} c^2 m_e = \frac{1}{2} A_{dom} m_p c^2 \beta_{sh}^2 \quad (4)$$

and

$$\gamma_{sh,inj} c m_e = \frac{A_{dom}}{Z_{dom}} m_p c \beta_{sh} \quad (5)$$

So between these two energies the energy density of CR electrons runs down by a factor of

$$\frac{2}{\beta_{sh}} \frac{1}{Z_{dom}} \quad (6)$$

in the first step. Here we use the observations of a spectral index of about E^{-3} implying that the energy content above a given energy runs as E^{-1} , so here giving a factor of about 20, with the observed $\beta_{sh} = 0.1$ (see ASR18 [43]).

There is an observational check on this, as the electron energies required to explain the radio observations of RSNe need to be above that first energy: We observe the emission at a frequency of 5 GHz, at a magnetic field of order Gauss requiring a Lorentz factor of $\gamma_e \simeq 30$, while $\gamma_{e,sh}$ for protons is about 10, so well below this. However, this argument implies that the emission should have a cutoff on the low frequency side, perhaps visible somewhat early in the emission phase and at lower frequency, such as 400 MHz. It also implies that at that stage of the emission there are constraints for what ions could possibly dominate to explain the emission, implying that in this numerical example $A_{dom} \lesssim 3$, eliminating basically all common elements other than Hydrogen.

In the second step, using a spectrum of $p^{-7/3}$ (see ASR18 [43]) the electrons reduce their energy in that range, where the protons do not contribute anything. Being below relativistic, so up to the energy of the proton rest mass (or dominant ion again) the factor is

$$\left(\frac{Z_{dom}}{\beta_{sh}} \right)^{+1/3} \quad (7)$$

which is about 2, using the same data again, with protons. So the CR electron energy density is reduced by a combined factor of $k \simeq 40$ when their momentum reaches that of the relativistic protons, where this factor is determined by observations. Already Allen & Kronberg (1998) [26] mentioned 40 as a possible value for k .

The argument makes it obvious that other sources, for which β_{sh} is smaller, contribute even less. That in turn implies that the combination of various sources contributing to electrons and protons reduces the electron net contribution even more, down to the observed factor of 1 in 100. All this starts with the energetic electrons having exactly the same energy density as the dominant ions in the shock, due to charge conservation. To the degree that protons have a strong contribution from ISM-SN-CRs, which have a slightly steeper spectrum than the most common wind-SN-CR component as well as

slower shocks, this suggests that at moderate energies the CR electrons have a spectrum slightly flatter than protons.

3.2. The magnetic field in the SN-shocked wind, and the implications

All this suggests that $k = 40$ is appropriate; covering this range of added assumptions implies an uncertainty of order $10^{\pm 0.2}$. This leads to a correction factor of 4.29 over the magnetic field values listed in Allen & Kronberg (1998) [26], and repeated above. However as we argued above, that the shock must have slowed down significantly already from its free expansion phase through the wind, and used the ISM-Sedov volume fraction of the shocked shell of $1/4$, we need to recognize that the magnetic field is likely to have been squashed by a new reverse shock pushed back through the material, giving the magnetic field an extra factor of 4, effectively cancelling the factor of 4.29. The magnetic field which we wanted to test was the value before any additional enhancement, still in the pure wind-shock mode; therefore we should reduce the magnetic field value obtained by a factor of 4, coming back to the original numbers by Allen & Kronberg (1998) [26]. This supports the argument by Allen & Kronberg (1998) [26] to give their magnetic field value without such an uncertain correction.

The average of the last column is 16.0: Using the calibration from Allen & Kronberg (1998) [26] and their flux density values we can also estimate the corresponding value of $\langle \log\{B \times r\} \rangle$ from the table in Fenech et al. (2010) [64], who did not include a separation of thermal and non-thermal emission, nor any absorption. However, to within the errors, we obtain the same number with a larger scatter confirming the analysis done by Allen & Kronberg (1998) [26]. Using the specific numbers here, a factor of $10^{0.1}$ higher than in ASR18 [43], gives for the *ankle* energy

$$E_{ankle} = Z 10^{17.6 \pm 0.2} \text{ eV}, \quad (8)$$

with the larger error due to the systematics, and now using eV for energy as is custom in the CR community.

Observations of the CR spectrum, mass composition and arrival direction anisotropy between *knee* and *ankle*, and to higher energies above the *ankle*, such as in Aab et al. (2017a, b, 2018) [1–3], Abbasi et al. (2018a, b, c) [8–10] and Abeysekara et al. (2018a) [14] will allow us to discern the details of highest energy tails of GCRs and the transition to extragalactic CRs.

Two questions remain, (i) whether the plasma wind maintains its magnetic profile $B_\phi \sim r^{-1}$ (Parker 1958, Weber & Davis 1967, [121,142]), and (ii) whether the SN-shock slows down. We have shown in ASR18 [43] from simple estimates of the ram-pressure in RSG star winds, and BSG star winds, that a RSG wind shell may be an order of magnitude smaller than a BSG star wind shell. That difference entails (see for a detailed estimate ASR18 [43]) that both in RSG star winds as in BSG star winds the SN-shock has the chance to race all the way to the wind shell, before converting into a more Cox-like Sedov expansion (Cox 1972 [58]; a Sedov expansion implies conservation of energy, Sedov 1958, [125]) through the wind shell and outer medium; the sparse data on velocities (e.g. Fenech et al. 2008, 2010 [63,64]) show that all measured velocities are below $0.1 c$, usually far below. In the data listed above in Table 1 there is no hint of any correlation between size and spectral index. Just from simple mass function arguments, the ratio of RSG star explosions to BSG star explosions is expected to be of order 1 to 2; however, in RSG star wind shells the density is far higher than in BSG star wind shells. Therefore the cooling is much more efficient. This implies that we have two development phases: First we have the racing phase, when the SN-shock goes through the plasma wind; for RSG star winds we may have an intermediate wind-Sedov phase (see ASR18 [43]); then we have the cooling phase, when the shock hits the outer shell, and the shock region transforms rapidly from a Sedov-like shock to a cooling shock. Both these stages for RSG star explosions are much shorter than for BSG star explosions. Consistently with such an expectation, in these data the typical size is about $1 pc$, with only 1 source at about $0.1 pc$, which may be a RSG star explosion, or a BSG star explosion in a very high pressure environment.

In ASR18 [43] we also derived the required piston mass to keep driving the shock; the number we obtained from γ -ray line observations was about $0.1 M_{\odot}$. The question is whether this could be the ^{56}Ni mass derived from optical observations (Maeda et al. 2010; Hamuy 2003; Utrobin et al. 2017; Nakar et al. 2016; Lusk & Baron 2017, [75,102,103,119,134]). Extrapolating from lower mass stars this seems possible, however, the numbers derived are highly model dependent, so for instance adopt usually 1D modelling rather than 3D modelling (for a 3D model see Utrobin et al. 2017) [134], so plumes of heavy elements cannot easily be accounted for (e.g., Biermann et al. 1992 [36], Wesson et al. 2015 [144]): Using just the energy in the ^{56}Ni decay chain ($^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$, e.g., Lusk & Baron 2017 [102]) should allow reliable numbers barring any issues with radiation transfer. We note (following again ASR18 [43]) that the mass suggested by the γ -ray line observation is certainly sufficient to drive a SN-shock all the way out to parsec scale radial distances in BSG star plasma winds, and do so at maximal velocity: the mass accumulated in a BSG star wind can be written as

$$\Delta M_{BSG,wind} = 10^{-2.3} M_{\odot} \frac{\dot{M}_{\star-5}}{V_{W,8.3}} \frac{r}{\text{pc}}, \quad (9)$$

where $\dot{M}_{\star-5}$ is the mass loss of the star prior to the explosion in units of $10^{-5} M_{\odot}\text{yr}^{-1}$, and $V_{W,8.3}$ is its wind velocity in units of 2000 km/s. The mass loss is directly determined in modelling the radio observations of the radio supernovae (ASR18 [43] and all its references in its Tables 1 and 2), and the wind velocity is typical for such stars. This shows that a piston of $0.1 M_{\odot}$ could drive the SN-shock unimpeded to scales of order 10 parsec, as long as the ram pressure is sufficient to overcome the environment.

This allows another consistency test of our concept and its numbers: The kinetic energy should exceed the magnetic field energy significantly. A piston of $0.1 M_{\odot}$ at $0.1 c$ corresponds to 10^{51} erg, while the typical magnetic field strength of about $\simeq 5$ mGauss corresponds to $10^{49.5}$ erg $\ll 10^{51}$ erg, using the volume fraction of $1/4$ adopted above.

For the ram pressure we need to consider first the wind ram pressure against the outside medium, and then the SN-shock ram pressure. The wind ram pressure condition for matching the ISM pressure is

$$r < 30 \text{ pc } \dot{M}_{\star-5}^{1/2} V_{W,8.3}^{1/2} P_{ISM,-12}^{-1/2} \quad (10)$$

where $P_{ISM,-12}$ is the outside pressure in units of $10^{-12} \text{ dyn cm}^{-2}$, a typical number for the outside pressure in our Galaxy. The higher pressure in M82 would allow smaller sizes for the wind shell, but of course the local pressure where the SNRs are seen, may be lower than in the central region. A pressure 10^3 times higher would still allow the size scales observed for the SNRs in M82. The region where the SNRs are seen has been described as a ring of about 500 pc radius (Weliachew et al. 1984, Kronberg & Wilkinson 1975, and Kronberg et al. 1981, [88,89,143]). Inside that ring the pressure might be even higher. If the ISM-pressure inside that ring were two orders of magnitude higher, for instance, as argued in KBS85, then the maximal size would only be 3 pc, still somewhat larger than the SNRs seen.

The corresponding SN-shock ram pressure condition is

$$r < 10^{2.7} \text{ pc } \dot{M}_{\star-5}^{1/2} V_{W,8.3}^{-1/2} V_{SN,-1} P_{ISM,-12}^{-1/2} \quad (11)$$

where $V_{SN,-1}$ is the shock speed in units of $0.1 c$. However, we also need to double-check when the mass accumulated outside within the extra radial range Δr slows down the progression of the shock, and that is given by

$$\left(\frac{\Delta r}{r} \right) = 10^{-0.7} M_{pist,-1} r_{pc}^{-3} n^{-1} \quad (12)$$

where $M_{pist,-1}$ is the mass of the piston in units of $0.1 M_{\odot}$, r_{pc} is the radius in pc when the SN-shock hits the outer medium, and n is the outside medium density in units of cm^{-3} . That implies that

once the SN-shock hits the wind shell and outside medium at full speed, the shock slows almost immediately to the Sedov stage, and only shortly later to the cooling phase. Adding in the mass accumulated in the wind does not modify this conclusion significantly. Nothing earlier slows down the SN-shock in a BSG star wind.

It follows that the *knee* energy predicted here is

$$E_{knee} = Z 10^{16.0 \pm 0.2} Z \text{ eV}, \quad (13)$$

We conclude that to within the errors these numbers on the product of radial scale and magnetic field in the table 1 and in tables 1 and 2 in ASR18 [43] are the same, supporting our argument, that in these examples the SN-shock pushed out without losing significant strength, and so maintaining these energies. Also, all of these examples in M82 are consistent with being BSG star explosions. All of the SNRs seen in M82 are consistent with being in the slow-down phase, after the SN-shock has hit the wind shell or other environment.

4. The origin of high energy Galactic cosmic rays

As we discussed and have shown above: RSG star explosions produce high energy (HE) Galactic cosmic rays (GCRs), i.e. energies around the *knee*, with a near normal abundances but not to the highest energies, and BSG star explosions give HE GCRs with all heavy elements enhanced and to the highest energies for GCRs. If our simple picture, deduced above, is correct, that RSG star explosions just terminate earlier, at a radius about 1/10 of that of BSG star explosions; the anti-proton data (ASR18 [43]) in our Galaxy suggest, that the RSG star explosions run their shock down in velocity, while the BSG star explosions hit their respective wind shell at full speed. We note that this distinction may be different in the galaxy M82, due to the higher environmental pressure. Therefore the characteristic energies, E_{knee} and E_{ankle} are maintained only for the BSG type of explosion. It ensues that at the highest CR energies, RSG star explosions contribute less than the BSG star explosions. Since in our model these energies scale with nuclear charge number Z , at a down-turn of the spectrum, near the *knee* the heavier elements go into dominance (see CR-IV [132]), and at the final cutoff, at the *ankle* energy, protons will disappear very much earlier than Carbon, Oxygen or heavier elements such as Iron (see Fig 6 in CR-IV, as well as Fig.1 in ASR18 [43,132]). We emphasize again, that the observed characteristic energies E_{knee} and E_{ankle} are directly reproduced by two independent data sets on RSNs and SNRs. This is based on RSNs in other galaxies, and SNRs in the starburst galaxies M82, without invoking any special parameter to be adjusted. The two data sets agree well within the errors. The spectrum both below and above the *knee*, can be explained with a combination of *Diffusive Shock Acceleration* (DSA) and *Stochastic Shock Drift Acceleration* (StSDA), as shown first in CR-I, CR-II, CR-III, and CR-IV, rederived in ASR18 [37–39,43,132], all based on earlier work by Drury (1983), Jokipii (1987), Völk & Biermann (1988), [62,82,138] and others as cited in CR-I, and ASR18 [37,43]. One consequence is that most interaction happens in the wind-shell, when the SN-driven shock hits (e.g. Biermann et al. 2001 [40]). In ASR18 [43] we discussed a number of consequences, that allow this concept to be tested with the spectra of secondary particles. Here we just note that the concept entails that the γ -ray -spectra of the Galaxy should reflect this early interaction, showing evidence for a spectrum of mostly $E^{-7/3}$ from the 4π component in wind-SN-CRs, and a weaker polar cap component of E^{-2} : A thorough analysis of the Fermi data already demonstrates that the data require two such spectral components (de Boer et al. 2017 [48]). HAWC (High Altitude Water Cherenkov Observatory) and HESS (High Energy Stereoscopic System) data are fully consistent with this prediction of a dominant 4π component (e.g. Nayerhoda et al. 2018 [120]). At higher γ -ray energies the spectrum produced is predicted to become flatter due to the emergence of the polar-cap component with E^{-2} in wind-SN-CRs (CR-IV [132]). Other new data, e.g. from AMS (Alpha Magnetic Spectrometer on the ISS) or HAWC, such as the spectra of various elements and secondary and primary contributions to Ni in cosmic rays (ASR18, Alfaro et al. 2017, Aguilar et al. 2017, 2018a, b [16–18,23,43]) can also be used as further tests.

However, there are a number of unanswered questions with this simple picture:

1) Very rarely we do have Gamma Ray Bursts (GRBs) in any star forming galaxy, at a rate of order 10^{-2} of massive stars. There is no question again, that they accelerate particles to high energy. Where is their contribution from GRBs in our own Galaxy? Could they contribute also below the *ankle*? Or is this already part of the *extragalactic contribution*, as argued in many papers, such as Milgrom & Usov (1995, 1996) [108,109]; Vietri (1995, 1996, 1998) [135–137]; Waxman (1995), Miralda-Escudé & Waxman (1996), Waxman & Bahcall (1997) [115,140,141]; Zhang & Mészáros (2004) [146]; Piran (2004) [122]. In ASR18 [43] we proposed that the compact radio source 41.9+58 in the starburst galaxy M82 (KBS85 [90]) is in fact the result of a recent merger of two stellar black holes (BHs), with a concurrent GRB (see Muxlow et al. 2005 [118], who argued first for a misaligned GRB for this source). The argument then proceeds to propose that this BH merger could explain the Ultra High Energy CR (UHECR) particles detected by the Telescope Array (TA) detector (Abbasi et al. 2014, 2018a [7,8]; and as cited in Biermann et al. 2016 [42]). Statistically GRBs do not seem to contribute much to UHECRs (Meli et al. 2008, Abbasi et al. 2012, Albert et al. 2017a, [6,20,106]). Meli et al. (2008) [106] also argued that GRBs in simulations and using a diffuse model do not contribute significantly to the UHECR population. All this depends on the model assumptions, and so may not be in contradiction.

2) There are many arguments in support of the sources of UHECRs from radio galaxies (e.g., Ginzburg & Syrovatskij 1963, Hillas 1984, Biermann & Strittmatter 1987, Meli et al. 2008, [35,71,80,106]), with a special interest in the case, when their relativistic jets are pointed at us, visible in the form of flat-spectrum-radio quasars (FSRQs) or blazars (Kadler et al. 2016; Kun et al. 2017, 2018; Aartsen et al. 2018a, b, [4,5,83,96,97]): There are now a total of nine candidate identifications for high energy neutrino events with FSRQs (see also the lectures of F. Halzen at Erice 2018 [74]), many of them suggestive of an ongoing merger of two super-massive black holes (Gergely & Biermann 2009, Caramete & Biermann 2010, Kun et al. 2017, [52,70,96]). One of these candidates, TXS0506+056 is the most convincing, since it shows evidence for several neutrino events. To make HE neutrinos requires the acceleration of HE and plausibly UHECR particles first, so this tentative finding allows the speculation that mergers of super-massive black holes may lead to ubiquitous production of UHECR particles. This entails that UHECR production is highly episodic. Do these sources also contribute below the *ankle*?

3) These BSG explosions can yield the energy, but can the CRs produced actually reach us? This is especially an issue for electrons and positrons: in ASR18 we argued that we need electrons up to 30 TeV in the source region; HESS has now detected electrons at 20 TeV, so far published only on its website [79], and in conference proceedings. The CR electron spectrum shown on the HESS website is consistent with our 2009 prediction (Biermann et al. 2009 [41]) of at lower energies first $E^{-10/3}$, then E^{-3} , and last, at the highest energies, E^{-4} , all based on the idea that many sources contribute under lots of losses (Kardashev 1962 [84]); at the highest energies the observed spectrum is slightly flatter than E^{-4} , possibly due to local and/or recent nearby sources. We note that the synchrotron loss time of electrons at 20 TeV is of order $3 \cdot 10^4$ yrs (using a magnetic field strength of order $5 \mu\text{Gauss}$: Beck et al. 1996 [31]; a crude estimate of $5 \mu\text{Gauss}$ was first made in the 1940s), implying a source rather close by (as has been argued by many, e.g., Yüksel et al. 2009 [145]), or a very anisotropic transport to allow larger distances; an alternate way of phrasing this speculation could be that the magnetic fields are extremely structured allowing some transport over large distances.

4) The relative contribution of CR particles from RSG star explosions and BSG star explosions at low energy is about 4:1, following Binns et al. (e.g. Murphy et al. 2016 [116]); what is it at high energy? The anti-proton data suggest, that the RSG star explosions shocks run out of steam, and so that RSG star explosions in our Galaxy contribute much less at the maximal energies than the BSG star explosions. This may imply that the piston mass in RSG star explosions is smaller than in BSG star explosions, consistent with a naive interpretation of the ^{56}Ni data:

5) Can the ^{56}Ni mass derived from optical observations (Hamuy et al. 2003, Maeda et al. 2010, Nakar et al. 2016, Lusk & Baron, 2017, Utrobin et al. 2017, [75,102,103,119,134]) be identified with the piston? The numbers seem to match rather well, but have not been derived for BSG star explosions, and rely mostly on rather simple 1D models, as we discussed above, and of course on using the bolometric

light-curve; and in fact, the numbers suggest a lower mass for RSG stars, as speculated above. We need to emphasize that we do not actually know the explosion mechanism for very massive stars, be it due to neutrinos (e.g. Bethe 1990 [34]), magnetic fields (e.g. Bisnovatyi-Kogan 1970, Bisnovatyi-Kogan et al. 2008 [44,45]), or - a newly worked out suggestion - quark deconfinement (Fischer et al. 2018 [67]) as the engine.

6) Do SN Ia explosions contribute anything to the observed CR particle population? The D^6 scenario seems to be favored now (Shen et al. 2018a [129]; D^6 here stands for *Dynamically Driven Double-degenerate Double-detonation*), especially with now also identifying some dwarf stars remaining from SN Ia explosions (Shen et al. 2018b, Raddi et al. 2018 [123,130]) in the Gaia data. The radio data (e.g. Dickel et al. 1991 [59]) and the interpretation of the radio and X-ray data (e.g. Chevalier 1982 [53]) demonstrate unequivocally that these explosions do accelerate energetic particles (Bykov et al. 2018 [50]). But what do they contribute to what is observed?

7) Pulsars and pulsar wind nebulae are directly observed to accelerate particles to high energy, and for one there is even a possible hint of neutrinos (TeVPA 2018 IceCube lectures; e.g. Aliu et al. 2014 [24]). What is their contribution? The high energy gamma data clearly demonstrate that they produce energetic particles very significantly, but they cannot contribute easily to the observed positrons (Yüksel et al. 2009; Abeysekara et al. 2017 [13,145]).

8) Relativistic SNe: this is amply discussed in Bykov et al. 2018 [50], in ASR18, and in many earlier papers cited therein. They surely contribute, as they are a variant of GRBs; however, is their contribution mostly at the very highest energies, and what ratio to GRB contributions do they show?

9) Active single and binary stars: Any massive star with a powerful wind contributes (Seo et al. 2018 [128]). Microquasars are binary stars, as are all massive stars (Chini et al. 2012, 2013 [54,55]). Micro-quasars surely produce energetic particles and cosmic rays (e.g. Heinz & Sunyaev 2002, Mirabel 2004, 2011 [77,110,111]). So all of the final evolutionary stages will be active contributors to energetic particles (e.g. Vulic et al. 2018, Abeysekara et al. 2018b [15,139]). But is their contribution discernible in the CR data?

10) Neutron star and stellar mass BH mergers; as this may lead to a GRB, as observed, they clearly can contribute (Abbott et al. 2017a, b; Albert et al. 2017b [11,12,21]).

11) Transport out of the Galaxy? Radio data allowed Heesen et al. (2018) [76], and Krause et al. (2018) [85] to show that CR transport is typically convective, i.e. in a galactic plasma wind. They give a threshold condition in the form of star formation rate per area (see also Rossa & Dettmar 2003 [124]). This confirms some very old ideas, going back to Weber & Davis (1967) [142], Parker (1958) [121] and even earlier notions in the late 1940s.

12) A CR contribution from the wind-shock of the Galactic plasma wind? This has been explored repeatedly (Jokipii & Morfill 1987 [81]), most recently by Merten et al. (2018) [107]; they find that such a contribution is possible.

13) Neutrino production in the Galaxy? The IceCube and Antares observations begin to constrain the models (Albert et al. 2018 [22]). The γ -ray data already suggest plausible models, all consistent with the concept here, that interaction is dominant when the SN-shock hits the wind-shell. Analogously to our comments on diffuse γ -ray emission ensues that there should be two underlying spectra of neutrinos, one at $E^{-7/3}$ from the 4π component, and at higher energy a lower E^{-2} from the polar-cap component (CR-IV [132]): These emission spectra have a transition at an energy which is not well determined right now. At TeV energies we cannot easily separate the RSG and BSG contributions, where the BSG star contributions may or may not dominate the neutrino emission. The stronger interaction in the RSG star explosions leading to anti-protons in our model proposed may push the transition energy to a higher value in the observations summed over a line of sight.

The overall diffuse Galactic neutrino emission is predicted to show a sharp turn-off of both components near $1/20$ of the *knee* energy for protons, so here

$$E_{v\text{off}} = 10^{14.7 \pm 0.2} \text{ eV}, \quad (14)$$

IceCube will surely be able to test this prediction in the future.

14) What is the explosion mechanism, and do we obtain a BH every time, or most of the time, when BSG stars explode? What is the nature of the piston? The innermost layers that get ejected come from a zone just outside the budding black hole, may reflect on the situation there, as regards density, pressure, E.O.S, and magnetic fields. Are there some stars that produce a black hole without any significant explosion at all (see Mirabel 2017a, b, c [112–114])? Do we have a chance to learn about BH physics from these explosions?

5. Summary

Our main task that we set ourselves was to check whether the characteristic energies implied by the numbers for radius, magnetic field, and shock velocity deduced from Radio Super Nova (RSN) data (listed in ASR18 [43]) can be confirmed with the observations of the compact sources, interpreted as Super Nova Remnants (SNRs) in the starburst galaxy M82 (KBS85, Allen & Kronberg 1998, Allen 1999, [25,26,90] as well as earlier and later references): The answer is positive: The energies for *knee* and *ankle* seen in the Cosmic Ray (CR) data can be derived directly, without any free parameter, from these data. That supports the interpretation, that the observed CRs in the energy range from just below the *knee* all the way to the *ankle* derive directly from Blue Super Giant (BSG) star explosions. As BSG star explosions are suspected to produce black holes, and to drive the piston pushing out the shock giving rise to CRs, can we learn from CRs and their detailed properties about BH formation?

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