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COSMIC RAY ACCELERATORS IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

I point out a correlation between the ∼100 MeV–10 GeV gamma-ray emissivity and the historical star formation rate (SFR) in the Large Magellanic Cloud (LMC) ∼12.5 Myr ago. This correlation bolsters the view that cosmic rays (CRs) in the LMC may be accelerated by conglomerations of supernova remnants (i.e., superbubbles), although it cannot yet be ruled out that other objects—also residing in such high SFR regions—may be responsible for accelerating the particles: indeed, most energetic objects capable of accelerating CRs are expected to reside in high SFR regions.

Key words: cosmic rays – Magellanic Clouds – ISM: bubbles – ISM: supernova remnants

1. INTRODUCTION

The origin of Galactic cosmic rays (GCRs) is a century-old enigma. Superbubbles (SBs) have been proposed as plausible GCR acceleration sites due to their great power, scale, and duration (e.g., Bykov 2001; Parizot et al. 2004; Butt 2009). They are powered by the fast stellar winds and multiple powerful supernova explosions of massive stars in dense stellar clusters and associations. Although visible in the radio and X-ray bands, galactic SBs have not yet been positively detected in γ-rays even though the importance of their role in GCR acceleration has been inferred from GCR composition studies (Higdon & Ligenfelter 2005). It is, as yet, unclear what the precise acceleration mechanism within SBs may be, and thus it is important to have some observational grounding of the theoretical SB acceleration models (e.g., Ferrand & Marcowith 2010).

Recent evidence from very high energy observations of external galaxies with high star formation rates (SFRs)—i.e., in which almost all supernovae would be expected to occur within SBs created by previous generations of nearby overlapping supernova remnants (SNRs)—bolsters the conjecture that SBs may accelerate CRs. The M82 starburst galaxy has been detected by the VERITAS Collaboration (Acciari et al. 2009) and NGC 253 has been detected by the HESS observatory (Acero et al. 2009) in the TeV gamma-ray band. These detections appear to show that CRs are accelerated by conglomerations of SNRs in such galaxies, although it cannot yet be ruled out that other objects (e.g., pulsars) may contribute to, or perhaps even be responsible for, the detected gamma-ray emission. Indeed, most energetic objects capable of accelerating CRs are expected to reside in high SFR regions. Conglomerations of SNRs could also pre-accelerate CRs in SNRs by standard mechanisms (i.e., the first-order Fermi process) before they are advected toward a termination shock to undergo further re-acceleration. To better understand whether and precisely how SB may accelerate CRs, such objects merit further detailed study both within our Galaxy and in external galaxies.

In our own Galaxy, the fraction of supernovae exploding within SBs is estimated at being approximately 75% (Higdon & Ligenfelter 2005). In a starburst galaxy, this fraction would be substantially higher. Although isolated SNRs (and, indeed, other types of galactic objects such as pulsars, microquasars, etc.) may also accelerate hadrons to CR energies, to identify the sources of GCRs requires us to focus on the dominant accelerators of such particles. Even under the standard paradigm that SNRs are responsible for accelerating GCRs, the importance of SBs is inescapable as they contain the bulk of SNR mechanical power. This is true not only in our Galaxy, but especially so for the more active starburst galaxies. Isolated SNRs may, however, be important contributors to CR acceleration during the first few generations of SNR explosions in a given galaxy, before SBs begin to occupy a substantial fraction of the galactic volume.

In this paper, I provide some further evidence that the SBs associated with star-forming regions in the neighboring Large Magellanic Cloud (LMC) galaxy may be responsible for accelerating CRs there, as previously suggested by Butt & Bykov (2008) based on simple, but independent, energetic arguments.

2. GAMMA-RAY CORRELATION WITH STAR FORMATION HISTORY

The *Fermi* orbiting gamma-ray observatory has detected ∼100 MeV–10 GeV γ-ray emission from the LMC at 33σ significance and provided a spatially resolved view of γ-rays from this nearly face-on external galaxy (Abdo et al. 2010). The LMC's distance of 50 kpc and low inclination angle make it possible to compare the distribution of γ-ray emission with the underlying stellar population and interstellar structures, for a critical examination of the possible sites of CR acceleration there.

Fermi LAT observations of the LMC have found the brightest γ-ray emission centered near the 30 Dor giant H II region, with fainter γ-ray emission also detected in the northern part of the LMC. The γ-ray emission detected by *Fermi* shows little correlation with the total column density of the interstellar gas and the γ-ray emission appears to be coincident with massive star-forming regions. These findings indicate that CRs in the LMC are likely accelerated in massive star-forming regions and that the diffusion length of GeV-range CR protons in the LMC is relatively short (Abdo et al. 2010).

As a cautionary note, there are two known crab-like pulsars, PSR J0540−6919 and PSR J0537−6910, in the peak gamma-emission region near 30 Dor. One of them, at least, may be contributing some gamma flux. For PSR J0540−6919 the *Fermi* data indicate the possible presence of pulsations: in fact, a detection significance of 2.4σ for the pulsations is found (Abdo et al. 2010). The HESS observatory announced a preliminary detection of the pulsar wind nebulae of PSR J0537−6910 at TeV energies at the 31st International Cosmic Ray Conference

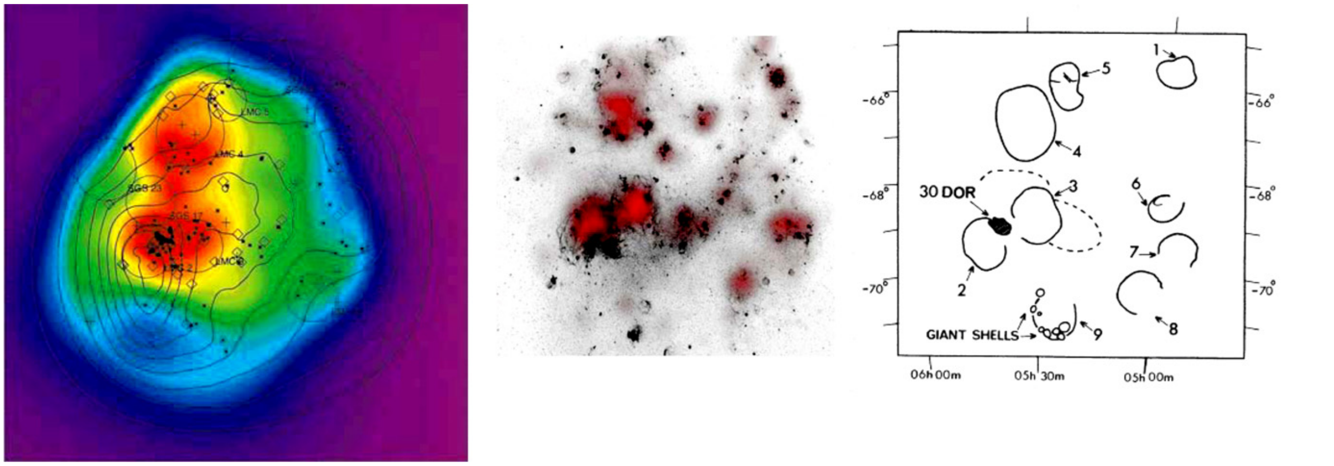

Figure 1. Left: luminosity map of the LMC from *Fermi* γ-ray telescope data for γ-rays with energy above 100 MeV. Contour lines indicate density of hydrogen gas and colors indicate local γ-ray emission per hydrogen gas atom. From Abdo et al. (2010). Credit: Abdo et al., A&A, 512, A7, 2010, reproduced with permission © ESO. Center: recent (age < 12.5 Myr) star formation activity in the LMC (in red) based on the analysis of Harris & Zaritsky (2009), overlaid on the Hα image of the LMC from the MCELS.[1] From Harris & Zaritsky (2009). Right: the approximate outlines of the supergiant shells in the LMC (LMC 1-9) shown as solid lines, from Meaburn (1980). Note the three-way correlation of the gamma-ray emission with the recent (<12 Myr) star formation activity (red, center panel) as well as with the supergiant shells there.

and, thusfar, a non-detection of 30 Dor, but further details have not yet been published (Torres 2009 and references therein).

Although Abdo et al. (2010) find a generally good correlation of the gamma-ray emissivity with the 30 Dor star-forming region in the central region of the LMC, there is an apparent "orphan" region of fainter γ-ray emission toward the north with no similar concrete counterpart yet identified by those authors. In order to better understand the origin of the gamma-ray emission (and thus the CRs) and their possible link with star formation, I compare the distribution of γ-ray emission with the historical star formation in the LMC.

A detailed study of the star formation history of the LMC is provided by Harris & Zaritsky (2009). The integrated >100 MeV γ-ray emissivity map of the LMC correlates very well with the SFRs 12.5 Myr ago in the LMC as deduced by Harris & Zaritsky (2009). Importantly, this is true not only for the γ-ray peak coincident with 30 Dor (as already noted by Abdo et al. 2010) but also for the fainter northern γ-ray emission—as well as for the extension to the west (Figure 1). Since the progenitors of supernovae in the LMC have a lifetime ranging from a few to ~15 Myr, the spatial coincidence of the γ-ray emissivity with the multiple sites of 12.5 Myr old star formation indicates that perhaps these conglomerations of supernovae (i.e., correlated in time and space) may play a role in the acceleration of CRs in the LMC, whether or not the individual constituent SNRs or SBs are identifiable or have yet been cataloged.

An examination of the Hα image[1] and H I column density map (Kim et al. 2003) of the LMC also reveals SBs and supergiant shells in regions where the SFR was high within the last ~12 Myr. Interestingly, the supergiant shells cataloged by Meaburn (1980) correlate well, both with the gamma-ray emission and with the star formation history of the LMC, as shown in Figure 1.

3. SUPPORTING EVIDENCE FOR CR ACCELERATION BY SBS IN THE LMC

Of course, the simple positional coincidence of SF regions, SBs, and gamma-ray emission does not, in itself, confirm that SBs play a role in CR acceleration. There is, however, also some further independent circumstantial evidence for the SB acceleration of CRs in the LMC. The observed thermal and kinetic energies of several SBs there are significantly lower than the stellar and supernova energy input—the so-called LMC SB "energy crisis." For example, observations of the SB "DEM L192" show that it contains only about one-third the energy injected by its constituent stars via fast stellar winds and supernovae (Cooper et al. 2004), most likely implying that the "missing" energy has gone into accelerating CRs (Butt & Bykov 2008). The presence of diffuse nonthermal X-ray emission (30 Dor: Bamba et al. 2004; DEM L192: Cooper et al. 2004; N11: Maddox et al. 2009) further bolsters this view. As yet, all other explanations of resolving the LMC SB energy crisis remain problematic (Butt & Bykov 2008 and references therein).

4. DISCUSSION

The above discussion supports the conjecture that the collective, interacting SNR shocks within SBs (produced by massive stars formed in the last ~15 Myr) may play a role in accelerating CRs in the LMC that are responsible for the >100 MeV γ-rays detected by the *Fermi* orbiting gamma-ray observatory.

The observed spectral cutoff around 10 GeV in the *Fermi* LMC data (Abdo et al. 2010) makes it challenging to understand the origin of the full range of CRs, if indeed the LMC hosts substantial quantities of super-TeV CRs. A gamma-ray emissivity map in the range 100 GeV–10 TeV would be very interesting and desirable: a large field-of-view TeV telescope with high sensitivity to large diffuse features would be ideal for this purpose, as suggested by Pohl et al. (2008).

It is important to note that the processes of CR acceleration in the LMC and our own Galaxy may well be somewhat distinct in their details. For example, the larger size of our Galaxy as well as its more pronounced spiral structure, extended halo, and central super-massive black hole, possibly involving magnetic or distributed re-acceleration processes (e.g., Colgate & Li 2001; Seo & Ptuskin 1994; Medina-Tanco & Opher 1993; Butt 2009), may make extrapolating results from the LMC to our Galaxy problematic. Such processes could also help explain the apparently larger CR diffusion length in our Galaxy as compared

[1] http://www.ctio.noao.edu/~mcels/

with the LMC, as well as the lower CR cutoff energy in the LMC—but see Abdo et al. (2010) for some further discussion regarding the possibility that the CR diffusion length in our Galaxy is also smaller than typically inferred and possibly consistent with the LMC results.

It may well be that SBs and associated star formation regions are only responsible for pre-accelerating GCRs to ∼10 GeV and the rest of the acceleration may occur by different processes, for example, via stochastic re-acceleration of CRs in the interstellar medium (e.g., Seo & Ptuskin 1994); or, in a galactic wind and/or halo (e.g., Zirakashvili & Völk 2006); or, perhaps, via magnetic re-connection (e.g., Colgate & Li 2004). In fact, very recently, intriguing hints of giant bubbles of cosmic rays extending to about ±10 kpc above and below the Galactic plane have been reported, coincident with the non-thermal microwave "haze" found in *WMAP* data and also with an extended region of X-ray emission detected by *ROSAT* (Crocker & Aharonian 2010; Su et al. 2010; Dobler et al. 2010).

Even though the GCR spectrum behaves approximately like a single power law which is usually—but not universally (e.g., see Ave et al. 2009)—interpreted as a "single-type accelerator" effect, the CR energy range considered in this conjecture is above ∼10 GeV, where solar modulation is no longer important. Note that the power law is imperfect: there is a small steepening of the GCR spectrum at the "knee," around 3×10^{15} eV, and there may be departures from a true power law at about 200 GeV nucleon^{-1} (Ahn et al. 2010). Thus, the *Fermi* results for the LMC do not conflict with our understanding of the GCR acceleration process(es) in our Galaxy, even if we subscribe to the "single-type accelerator" conjecture, since the *Fermi* LMC data studied are at energies <20 GeV (Abdo et al. 2010).

It should also be noted that any accelerator in which a fractional gain in energy, $(d \ln E)$, by some particles is accompanied by a fractional loss, $-(d \ln N)$, in the number of the remainder will yield the observed power law, $dN/N = -\alpha(dE/E)$—and $\alpha \sim 2$ is expected for any rigidity-dependent escape process, not just shock acceleration by SNRs and SBs (Colgate & Li 2001). Thus, a source CR spectrum with $\alpha \sim 2$ ought not to be a surprise and need not favor any particular model. It also need not imply a single-type of CR source for all CRs between 10 GeV and 10^{18} eV, or even all CRs between 10 GeV and 10^{15} eV. Indeed, recent detailed studies of the de-propagated GCR source spectra are problematic for the simple isolated-SNR origin of CRs hypothesis: the preferred source power-law index is found to be $\alpha \sim 2.3$–2.4 indicating a softer source energy spectrum, in conflict with most diffusive shock acceleration models presumed to operate in isolated SNRs (Ave et al. 2009), but possibly in agreement with the softer high-energy end of SB-accelerated CRs (Ferrand & Marcowith 2010). Similarly, a joint analysis of the propagation and composition of GCRs by Strong et al. (2007) also favors a source CR spectrum with $\alpha \sim 2.3$–2.4.

Further study of the γ-ray emissivity of the LMC, complemented by a detailed knowledge of star formation history and interstellar gas structure, will help localize where precisely CRs in the LMC are accelerated and how CRs diffuse into the interstellar medium. Deeper γ-ray data from *Fermi* and other observatories will also reveal whether the smaller outlying regions of star formation 12.5 Myr ago are eventually confirmed as γ-ray emitters. If the gamma-ray emissivity of the LMC is truly correlated with the star formation history there, then one may venture a prediction that these more minor regions of recent SF will likely be resolved in deeper *Fermi* observations. In particular, the western region near LMC 8 shown in red by Harris & Zaritsky (2009; at $\sim 05^{h}00^{m}$, $-70°30'$; Figure 1, central panel) should be resolvable from the more distant LMC gamma emission regions. In fact, the likely correlation—properly taking into account the differing amounts of target molecular material, of course—between all the recent SF regions (shown in red in the central panel of Figure 1) and the future locations of gamma-ray emission maxima in deeper observations ought to be carefully investigated.

Understanding the process of CR acceleration in the LMC will complement the theoretical investigations of the CR acceleration process at work in SBs (e.g., Ferrand & Marcowith 2010) and will allow us to construct better models, both for the LMC and for our own Galaxy.

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