Constraints on the Cosmic Rays in the Small Magellanic Cloud

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Observations of the Small Magellanic Cloud using the Energetic Gamma Ray Experiment Telescope on the Compton Observatory yield an upper limit (95% confidence) for gamma-ray emission >100 MeV of 0.5×10^{-7} photon/cm^{2}s. The expected flux if the cosmic rays are universal rather than galactic in origin is $(2.4\pm0.5)\times10^{-7}$ photon/cm^{2}s, only a third of which arise from cosmic ray electron interactions. Hence, the bulk of the cosmic ray energy density is almost certainly not metagalactic, and therefore galactic in origin.

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The Magellanic Clouds, being the closest galaxies to our own, naturally provide one of the best opportunities for the study of many different aspects of galaxies. Of particular interest here is the cosmic ray content. A long-standing, critical question in the study of the dynamics of our Galaxy is whether the origin of the bulk of cosmic rays is galactic or extragalactic. Although there exists evidence indicating that they are primarily galactic in origin, there are counter arguments for an extragalactic origin based on contributions from radio galaxies, quasistellar objects, and galactic winds (for a general discussion, see [1]). Ginzburg and Ptuskin [2] have noted that a definitive test of whether the bulk of the cosmic rays is galactic or universal is to compare the level of high-energy gamma-ray emission from these galaxies. Radio synchrotron observations provide information on the cosmic ray electron component, although the major energy component is the nucleonic one. Sreekumar and Fichtel [3] showed that, based on the synchrotron data, arguments regarding the expected magnetic field strength, and the assumption of the same cosmic ray electron to nucleon ratio as in our local solar neighborhood, the Small Magellanic Cloud (SMC) would be expected to have a cosmic ray density well below that in our Galaxy. This finding is consistent with the concept that the SMC is in a state of irreversible disintegration, in agreement with the independent experimental findings by Mathewson, Ford, and Visvanathan [4] and the tidal interaction model of Murai and Fujimoto [5].

Since high-energy gamma rays are created in the interaction of cosmic ray nucleons and electrons with interstellar matter, a study of these photons represents a more direct estimate of the cosmic ray density. Sreekumar and Fichtel [3] calculated the expected high-energy gamma-ray emission for the cases of quasistable equilibrium, a universal cosmic ray density, and the disrupted state described earlier. The predicted flux for each of these cases is different. Thus, a meaningful test of the underlying model is possible by comparing with recent observations. Quasiequilibrium involves a dynamic balance between the attractive gravitational pressure and expansive pressures arising from cosmic rays, interstellar gas, and magnetic fields. It is expected to exist if the external pressures are small and cosmic ray sources are adequate. See Parker [6] for a full discussion.

For comparison, this is not the situation in the Large Magellanic Cloud (LMC), which is expected to be in quasistable equilibrium with a cosmic ray density level similar to that in the local region of our Galaxy [7]. Using recent LMC observations by the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Observatory, Sreekumar *et al.* [8] have in fact shown that the high-energy gamma-ray emission from the LMC is consistent with the calculations assuming a quasistable equilibrium scenario. However, the measured flux is also consistent with a universally constant cosmic ray distribution. Thus, a definitive test does not exist there. For completeness, it should be noted that in principle it should be possible to look for variations of the cosmic ray density in our Galaxy, but this is complicated by the interpretation of the data resulting from our location in the galactic plane as well as uncertainty in estimates of the molecular hydrogen density [9,10].

In this paper, the results of a high-energy gamma-ray observation of the SMC by the EGRET on the Compton Observatory are reported. The experimental findings are discussed in the context of the theoretical predictions. Further, the conclusions reached here are applied to the results recently reported for the LMC by Sreekumar *et al.* [8], allowing a more definitive deduction to be made on its state.

A detailed description of the EGRET instrument and its general capabilities is given by Hughes *et al.* [11] and Kanbach *et al.* [12,13]. The results of the instrument calibration, both before and after launch, are given by Thompson *et al.* [14]. Briefly, EGRET has an anticoincidence scintillator dome to discriminate against charged particles, a spark-chamber particle-track detector with interspersed high-Z material to convert the gamma rays into electron-positron pairs, a triggering telescope which detects the presence of the pair and determines that the particles have the correct direction of motion, and a NaI(Tl) crystal as an energy measurement device. The telescope covers the energy range from 30 MeV to over 30 GeV. The effective area is about 1.5×10^3 cm^2 from 0.2 to 1.0 GeV, and lower outside of this range. The instrument is designed to be free of internal background, and the calibration tests have verified that it is at least an order of magnitude below the extragalactic gamma radiation. Hence, the only other significant radiation in addition to individual sources is the diffuse galactic radiation from our Galaxy and extragalactic radiation.

Typical EGRET observing periods were two weeks during the early part of the mission. There were three separate observations of the SMC from 25 July to 8 August 1991, 19 September to 3 October 1991, and 27 December 1991 to 10 January 1992. The EGRET axis was 25°, 14°, and 20°, respectively, from the direction of the SMC, and so the second observation provided the best exposure.

The galactic diffuse gamma radiation was modeled assuming that the emission arises from the interaction of galactic cosmic rays with interstellar gas in our Galaxy. The source functions for the various interaction processes (nucleon-nucleon interaction and electron bremsstrahlung) that give rise to gamma-ray emission were derived from the current best understanding of the cosmic ray spectrum and nuclear cross-section calculations [7,15,16]. Additional details of the diffuse gamma-ray model will be available in a forthcoming paper [9]. The model also included a constant isotropic component of cosmic origin. The value of the isotropic component used was adopted from Thompson and Fichtel [17] as 1×10^{-5} photon/(cm^{2}s sr) for energies >100 MeV. Another small component [0.2×10^{-5} photon/(cm^{2}s sr)] is also added to account for contributions from gamma rays arising from inverse Compton interaction of low-energy photons with relativistic cosmic ray electrons in our Galaxy. The observed intensity of radiation matches the model prediction quite well over the complete field of view. No significant deviation was found in the SMC region. Using the combined data from the three observations, the observed upper limit (95% confidence) for gamma-ray emission from the SMC at energies >100 MeV is determined to be 0.5×10^{-7} photon/cm^{2}s.

Unlike the LMC, the SMC is thought by some not to be in equilibrium. McGee and Newton [18] reexamined their 21-cm line data from Parkes and concluded that there are four separate velocity components in the neutral hydrogen profile, of which the +134 and +167 km s^{-1} (heliocentric velocities) components arise from the more dense regions and are both present throughout most of the cloud (Fig. 8 of their paper). Numerous studies have been undertaken in recent years to determine the thickness of the SMC along the line of sight. Using Cepheids in the SMC, Mathewson, Ford, and Visvanathan [4] determined a line of sight depth of 20 to 30 kpc. They proposed a two-component model of the SMC with a nearer low-velocity component and a more distant high-velocity component, consistent with the tidal-interaction model of Murai and Fujimoto [5] involving a close encounter with the LMC about 2×10^8 yr ago. They conclude further that the SMC is in a state of irreversible disintegration. From their study of the 63 SMC Cepheids, Caldwell and Coulson [19] also arrived at a similar conclusion regarding the depth but, contrary to the Mathewson, Ford, and Visvanathan picture, they interpret the SMC primarily as one body with a large velocity gradient from the northeast to southwest, superimposed on which is an arm of material located closer to us in the southwest. In contrast, Welch *et al.* [20], using infrared photometry of Cepheids, conclude that the SMC is not in the process of irreversible disintegration. Thus, there is no universal agreement on the question of stability, but a disrupted state seems more likely for the SMC.

The high-energy gamma-ray emission to be expected from the SMC for three cases has been calculated by Sreekumar and Fichtel [3]. The results for the flux above 100 MeV are 2.4×10^{-7} photon/cm^{2}s for the universal or metagalactic cosmic ray case and 1.2×10^{-7} photon/cm^{2}s for the quasiequilibrium case. The contribution from cosmic ray electrons is estimated to be a third, the rest being from cosmic ray nucleon interactions. Further, based on the synchrotron radiation data, they concluded that the SMC cosmic ray density is not at a level consistent with quasistable equilibrium. If the level that they deduced in this way is the one that exists in the SMC the expected high-energy gamma-ray flux above 100 MeV is much lower, $(2-3)\times10^{-8}$ cm^{-2}s^{-1}, with the range in values being associated with the part of the matter that is assumed to be relevant for the disintegrating case. The uncertainty in all of these numbers is estimated to be about 10%. Any point source contribution has to be added to these estimates, but that addition is expected to be small.

The results reported here indicate clearly that the cosmic ray density observed in the local region of our Galaxy is not metagalactic. Hence, this long-standing question seems to be answered since the conclusion is based only on the amount of matter present, the known cosmic ray density in our Galaxy, and measured nuclear cross sections. The result is consistent with the current theoretical beliefs that there is sufficient energy within a galaxy to fill it with cosmic rays, but that it is much more difficult to envision a means of filling the whole Universe or the Local Group with cosmic rays at the energy density level seen in the local region of our Galaxy.

It also seems that the observed upper limit is not consistent with quasistable equilibrium conditions in the SMC, although this conclusion is less compelling because of the statistical limitations of the gamma-ray data. Together with other indications, the results suggest that the SMC is not in quasistable equilibrium, and is likely to be in a state of disruption. The upper limit is above the level suggested by Sreekumar and Fichtel for the disrupted state based on synchrotron data and the assumption that the SMC is disrupted. A considerably longer exposure that led to a significantly decreased upper limit could provide a definitive statement on the SMC not being in quasistable equilibrium. Thus, based on the conclusion that cosmic rays are not metagalactic, it appears that cosmic rays in the SMC are present at a much lower density on an average than in our Galaxy.

With the result obtained here for the SMC effectively eliminating the metagalactic or universal cosmic ray hypothesis, it is now possible to reexamine the LMC result [8] and answer the questions that were mentioned above. If the cosmic rays are not universal then the LMC high-energy gamma-ray result can be interpreted as showing that the LMC is most likely in quasistable equilibrium since the gamma radiation is at the level expected for such a condition and would be much lower if it were not. The point source contribution, although unknown, would not be expected to be large enough to alter this conclusion.

In conclusion, it is possible to draw three conclusions from the EGRET high-energy gamma-ray observations of the SMC and the LMC. First, the bulk of the cosmic ray energy density is almost certainly not metagalactic nor universal, but is galactic in origin; otherwise, the high-energy gamma flux from the SMC would be much higher than the upper limit obtained from EGRET observations. Second, the results from the high-energy gamma-ray observation adds to the evidence that the SMC is in a nonequilibrium state. Third, with the elimination of the universal cosmic ray concept, the LMC high-energy gamma-ray data indicate that the LMC is most likely in quasistable equilibrium, with a cosmic ray energy density near the maximum that can be contained.

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