

ISOTROPIC GAMMA-RAY BACKGROUND: COSMIC-RAY-INDUCED ALBEDO FROM DEBRIS IN THE SOLAR SYSTEM?

IGOR V. MOSKALENKO^{1,3} AND TROY A. PORTER²

¹ Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA; imos@stanford.edu

² Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA; tporter@scipp.ucsc.edu

Received 2008 November 26; accepted 2008 December 23; published 2009 January 22

ABSTRACT

We calculate the γ -ray albedo due to cosmic-ray interactions with debris (small rocks, dust, and grains) in the Oort Cloud. We show that under reasonable assumptions a significant proportion of what is called the “extragalactic γ -ray background” could be produced at the outer frontier of the solar system, and may be detectable by the Large Area Telescope, the primary instrument on the *Fermi Gamma-ray Space Telescope*. If detected, it could provide unique direct information about the total column density of material in the Oort Cloud that is difficult to access by any other method. The same γ -ray production process takes place in other populations of small solar system bodies, such as Main Belt asteroids, Jovian and Neptunian Trojans, and Kuiper Belt objects. Their detection can be used to constrain the total mass of debris in these systems.

Key words: cosmic rays – diffuse radiation – gamma rays: theory – interplanetary medium – Kuiper Belt – Oort Cloud

1. INTRODUCTION

Studies of the outermost region of the solar system started in antiquity as documented by the historical record of comet observations (Kronk 1999). Among the oldest are Babylonian inscriptions referring to a comet of 674 B.C.E. The first proven observation of the 1P/Halley comet is recorded in the Chinese text *Shih chi* dated 239 B.C.E., and its revisits of the inner solar system have been recorded by subsequent generations of astronomers. However, ancient astronomers had very little knowledge about the origin of these comets. Only in 1950, based on observations of a handful of so-called long-period (LP) comets was the conclusion made that there is a huge reservoir of $\sim 10^{11}$ comets that surrounds the solar system at distances larger than $\sim 10^4$ AU (Oort 1950). Since that time the total number of identified LP comets has increased to ~ 400 (Marsden & Williams 2003). This reservoir is now known as the Oort Cloud (OC) and its outer edge is placed between 5×10^4 and 2×10^5 AU ~ 1 pc (Weissman 2000; Dones et al. 2004). The OC population is the least explored in the solar system because its extremely distant location from the Sun renders the detection methods used for objects such as Kuiper Belt objects (KBOs) ineffective.⁴

Perturbations due to the Galactic tide, passing stars, and giant molecular clouds alter the orbits of objects in the OC. The result is that a small fraction of these objects are injected into the inner solar system, appearing as LP comets. Such comets are the only members of the OC population that are available for study by astrophysical methods so far. Therefore, conclusions on the structure of the OC and composition of its bodies are mainly based on the studies of LP comets. As the comets are largely composed of ices, other OC bodies are assumed to have a similar composition. The sizes of the comet nuclei range between a few km and ~ 50 km. A population of bodies below a subkilometer size is terra incognita.

The OC is believed to be a remnant of the protoplanetary disk that formed around the Sun approximately 4.6 billion years ago. The total mass and geometry of the OC are determined by very indirect methods and rely mostly on computer-intensive simulations (e.g., Dones et al. 2004). The planetesimals comprising the OC initially coalesced much closer to the Sun, but gravitational interactions with giant planets ejected the protoplanetary material into the outer edge of the solar system (e.g., Morbidelli 2005). As the accretion and collision rates in the OC are extremely slow, it is believed that it contains the most pristine material left over from the epoch of planet formation.

A new method to study the populations of small solar system bodies (SSSBs, such as Main Belt asteroids (MBAs), Jovian and Neptunian Trojans, and KBOs) has been recently proposed by Moskalenko et al. (2008). It was shown that the cosmic-ray (CR)-induced γ -ray flux from SSSBs which are large enough for the CR cascade to fully develop in the rock (typically $\gtrsim 1$ m in diameter, the “thick-target” case) strongly depends on the size distribution of the SSSB populations and may be detectable with the Large Area Telescope (LAT), the primary instrument on the *Fermi Gamma-ray Space Telescope* (*Fermi*; formerly the *Gamma-ray Large Area Space Telescope* (*GLAST*)). The γ -ray spectrum from these processes is very steep with an effective cutoff around 1 GeV. If detected by the LAT, it can provide unique information about the number of objects with sizes down to a few meters in each system.

For objects with diameters below ~ 1 m, the CR cascade does not fully develop since the total column density of material is $\lesssim 1$ interaction length. In this “thin-target” case, the albedo γ -rays depend only on the total column density of material in a particular direction. The albedo spectrum has a shape characteristic of pp -interactions where the high-energy spectral slope is similar to that of the incident CR spectrum. Therefore, it is possible also using γ -ray observations to put constraints on the total amount of debris in each system.

The outermost frontier of the solar system, the OC, has a wide distribution on the sky. This is different to other populations of small bodies such as the MBAs, Jovian and Neptunian Trojans, and KBOs which are distributed near the ecliptic. The albedo γ -rays produced by CR interactions with debris in the OC

³ Also Kavli Institute for Particle Astrophysics, and Cosmology, Stanford University, Stanford, CA 94309, USA.

⁴ Here we mean the usual optical- and infrared-based methods relying on the detection of scattered solar radiation from the individual objects.

apparently contribute to the isotropic γ -ray background (IGRB), which is usually assumed to be extragalactic. A correct estimate of the γ -ray albedo of the OC is important for disentangling the truly extragalactic component. On the other hand, an estimate of the total column density of the dispersed material in the OC may shed light on the early history of the solar system and constrain planetary evolution models.

2. ISOTROPIC GAMMA-RAY BACKGROUND

The IGRB was first discovered by the SAS 2 satellite (Thompson & Fichtel 1982) and confirmed by EGRET (Sreekumar et al. 1998). The IGRB is thought to be a superposition of all unresolved sources of high-energy γ -rays in the universe plus any truly diffuse component. A list of the contributors to the IGRB includes “guaranteed” sources such as blazars and normal galaxies (Bignami et al. 1979; Pavlidou & Fields 2002), and potential sources such as galaxy clusters (Ensslin et al. 1997), shock waves associated with large-scale cosmological structure formation (Loeb & Waxman 2000; Miniati 2002), distant γ -ray burst events (Casanova et al. 2007), pair cascades from TeV γ -ray sources, and ultra-high-energy CRs at high redshifts (so-called Greisen–Zatsepin–Kuzmin cutoff). A consensus exists that a population of unresolved active galactic nuclei (AGN) certainly contribute to the IGRB inferred from EGRET observations; however, predictions range from 25% to 100% of the IGRB (Stecker & Salamon 1996; Mukherjee & Chiang 1999; Chiang & Mukherjee 1998; Mücke & Pohl 2000). A summary of the conventional contributors to the IGRB can be found in Dermer (2007). A number of exotic sources that may contribute to the IGRB have also been proposed: baryon–antibaryon annihilation phase after the big bang, evaporation of primordial black holes, annihilation of so-called weakly interacting massive particles (WIMPs), and strings.

The IGRB is a weak component which is difficult to disentangle from the intense Galactic foreground. Extensive work has been done (Sreekumar et al. 1998) to derive the spectrum of the IGRB based on EGRET data. A new detailed model of the Galactic diffuse emission (Strong et al. 2004a; Moskalenko & Strong 2000) leads to a new estimate of the IGRB (Strong et al. 2004b) which is lower and steeper than that found by Sreekumar et al. (1998); it is not consistent with a power-law and shows some positive curvature, as expected for an origin in blazars. But recent work has shown deficiencies in the understanding of the IGRB. Two more diffuse emission components originating nearby in the solar system have been identified: γ -ray emission due to inverse Compton scattering of solar photons by CR electrons (Moskalenko et al. 2006; Orlando & Strong 2007) and a γ -ray glow around the ecliptic due to the CR-induced γ -ray albedo of SSSBs (Moskalenko et al. 2008). The former has been detected in the EGRET data at a level consistent with predictions (Orlando & Strong 2008). Significantly, the level of emission from this process is comparable to the current estimate of the IGRB within 10° of the Sun’s path on the sky.

3. THE OORT CLOUD

Although an extensive literature exists on the origin, population, and dynamics of the OC, properties of the OC population are derived mostly from computer simulations and studies of the LP and Halley-type comets which are thought to originate in the OC. In this section, we give a brief overview of the structure of the OC relevant to the current investigation. For more detailed information, we refer the reader to the exhaustive books

and reviews (e.g., Brandt & Chapman 2004; Dones et al. 2004; Fernández 2005, and references therein).

Observation of a sharp spike in the number distribution of comets at near-zero but bound energies, representing orbits with semimajor axes exceeding 10^4 AU, led Oort to conclude that the spike, a huge near-spherical cloud of icy bodies at $> 2 \times 10^4$ AU (outer OC), had to be the source of the LP comets. Hills (1981) has shown that the apparent inner edge of the OC at a semimajor axis $a \sim (1-2) \times 10^4$ AU could be a selection effect due to the small probability of close stellar passages capable of perturbing comets at smaller distances. The number of comets that reside in the Hills cloud (inner OC) at semimajor axes of a few thousand AU could be significantly larger than in the outer OC. The inner OC could also serve as a reservoir that replenishes the outer OC stripped by an external perturber. Close passages of stars perturbing the inner OC could result in so-called “comet showers,” the extreme increases in cometary flux which last for a few orbital periods after the passage. One such shower may be responsible for a ~ 2.5 Myr period of increased bombardment of the Earth which produced the large Popigai (100 km) and Chesapeake Bay (90 km) craters and several smaller craters ~ 36 million years ago (Farley et al. 1998).

A possible clue to the existence and the structure of the inner OC could be the Halley-type comets. Dynamical simulations show that the source of these comets (Levison et al. 2001) is required to be a massive doughnut-shaped inner OC with median inclination between 10° and 50° . Yet, there could exist a third innermost region, the so-called *inner core* (Fernández 2005), which may span between the Scattered Disk component of the Kuiper Belt and the inner OC. The inner core may harbor a large number of comets and mass, but does not exhibit itself due to the lack of very close stellar passages. Dwarf planets 90377 Sedna and 148209 2000 CR₁₀₅ could be the first inner-core candidates.

Dynamical models put the total number of comets with $a \gtrsim (1-2) \times 10^4$ AU at $\sim 10^{12}$. Assuming an average mass for a comet of 4×10^{16} g, the total mass is estimated at $7 M_\oplus$. The more massive inner OC could harbor $\sim (2-13) \times 10^{12}$ comets, which yields a mass of $14-90 M_\oplus$. There is no information on the total mass and number of subkilometer-size bodies.

Even closer to the Sun, beyond Neptune’s orbit there is the Kuiper Belt. The KBOs are not uniformly distributed, with at least three dynamically distinct populations identified: the Classical Disk, the Scattered Disk with large eccentricities and inclinations, and “Plutinos” around the 3:2 mean motion resonance with Neptune at 39.4 AU. KBOs are distributed between 30 and 100 AU (Backman et al. 1995, and references therein). A majority of the KBOs have their orbits distributed near the ecliptic with FWHM of the order of 10° in ecliptic latitude (Brown 2001). The total mass of KBOs is estimated to be in the range $\sim 0.01-0.3 M_\oplus$, while the most often used value is $\sim 0.1 M_\oplus$ (Luu & Jewitt 2002). A summary of the mass and size distributions of KBOs, MBAs, and population of small bodies in Jovian and Neptunian Trojan families can be found in Moskalenko et al. (2008).

The mass and size distributions for populations of asteroid families or other SSSBs are thought to be governed by collisional evolution and accretion. Under the assumptions of scaling of the collisional response parameters and an upper cutoff in mass, the relaxed size distributions approach a power law $dN \propto r^{-n} dr$ (Dohnanyi 1969), where r is the radius of the body, and $n = 3.5$ for a pure Dohnanyi cascade. In reality, different populations of SSSBs show deviations from this index.

The dust particles and grains in the solar system are subject to many processes which produce a negligible effect on larger bodies; therefore simulations of the dynamics of the asteroid populations cannot tell much about the total mass of debris or the size distribution. The main forces acting on small particles are (e.g., Grün 2007): gravitation, radiation pressure which is directed outward from the Sun, the Poynting–Robertson effect which is essentially a drag reducing the orbital eccentricity and causing the particles to slowly spiral toward the Sun, sublimation, collisions among dust particles, plus interactions with the solar wind and magnetic field due to a small electric charge carried by grains which further complicates their dynamics. The relative effect of these processes is different across the range of particle sizes and number densities. Thus, it is very difficult to simulate the distribution of debris in the solar system. However, if the column density of the debris is large enough its distribution can be directly probed with the *Fermi*/LAT γ -ray telescope.

4. CALCULATIONS

Our previous calculations (Moskalenko et al. 2008) considered bodies large enough to be in the thick-target case. To calculate the CR-induced γ -ray albedo of SSSBs, the Moon spectrum has been used as a template and scaled according to the size distributions and densities of bodies in different populations, such as the MBAs, Jovian and Neptunian Trojans, and KBOs. The CR-induced γ -ray albedo spectrum of the Moon itself has been calculated by Moskalenko & Porter (2007) using a Monte Carlo code based on the GEANT4 framework. Most of the lunar γ -ray emission comes from the thin rim with a steep fall off with energy, essentially cutting off above 3–4 GeV. The central portion of the Moon disk has an even steeper spectrum with a cutoff above ~ 600 MeV. The model calculations are in excellent agreement with the EGRET observations of the Moon (Thompson et al. 1997; Orlando & Strong 2008).

For objects with sizes smaller than ~ 1 m the CR cascade does not fully develop; this is similar to CR interactions with a single nucleus with the produced γ -ray flux scaling linearly with the total amount of material in the interaction column. The γ -ray spectrum in this case is harder than the thick-target case with a spectral slope close to that of the parent CR nuclei. The γ -ray albedo of larger bodies has a soft spectrum which will also contribute to the total γ -ray flux $\lesssim 1$ GeV. Therefore, the total albedo spectral shape below/above 1 GeV will depend on the relative abundances of the debris material and the larger rocks.

Production of γ -rays in pp -interactions from the decay of neutral pions and kaons has been discussed in many papers (e.g., Stecker 1970; Badhwar et al. 1977; Stephens & Badhwar 1981; Dermer 1986a, 1986b, and more recently Kamae et al. 2006 and Kelner et al. 2006). We calculate the γ -ray flux using the method described in Moskalenko & Strong (1998) which is based on the work of Dermer (1986a, 1986b). For collisions involving nuclei, the corresponding cross section is multiplied by a factor $(A_1^{3/8} + A_2^{3/8} - 1)^2$ where A_1 and A_2 are the beam and target nucleus atomic numbers (Orth & Buffington 1976; Dermer 1986a), while the energy per nucleon is the kinematic variable. The accuracy of this method is sufficient for the current calculations.

Since oxygen is the most abundant element in the interstellar rock and ice, we calculate the production cross section of γ -rays for CR protons and alphas interacting with an oxygen target nucleus. The cross section is converted from nucleus $^{-1}$ to g $^{-1}$ units by multiplying by $N_A/16$, where N_A is Avogadro's

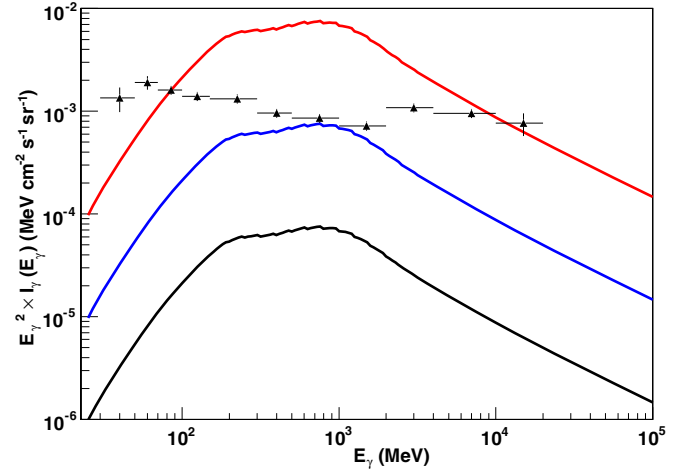


Figure 1. Intensity of the IGRB as derived from the EGRET data (Strong et al. 2004b). Curves are shown for the thin-target case for different column densities (top to bottom): 0.01, 0.001, 0.0001 g cm $^{-2}$.

Table 1
Debris Detection Limits in Different Asteroid Populations

Population	Semimajor Axis, AU	Total Mass, M_\oplus	Debris Detection Limit, M_\oplus
MBAs ^a	2.1–3.3	$\sim 6 \times 10^{-4}$	$\sim 4 \times 10^{-7}$
Jovian Trojans	5.2	$\sim 1 \times 10^{-4}$	$\sim (1.8\text{--}3.8) \times 10^{-6}$
Neptunian Trojans	30	$\sim 1 \times 10^{-3}$	$\sim 9 \times 10^{-5}$
KBOs ^b	30–50	~ 0.1	$\sim 1.3 \times 10^{-2}$
OC ^c	> 100	~ 100	~ 50

Notes.

^a Integral over the ecliptic longitude assuming average $d = 2$ AU.

^b Using $x = 10^{-4}$ g cm $^{-2}$, $d = 40$ AU.

^c Using $x = 10^{-4}$ g cm $^{-2}$, $d = 10^3$ AU.

number. The total γ -ray emissivity is obtained by integrating the respective production cross sections with the interstellar (unmodulated) incident spectrum of CR protons and alphas taken from Moskalenko & Porter (2007).

Figure 1 shows the spectrum of the IGRB derived from the EGRET data (Strong et al. 2004b) together with the γ -ray albedo of the OC debris (thin-target case) shown for different total column densities (top to bottom): 0.01, 0.001, 0.0001 g cm $^{-2}$. The latter can be compared with the total gas column density along the line of sight to the edge of the Galactic disk through the Galactic center: ~ 0.15 g cm $^{-2}$ assuming an average 1 H atom cm $^{-3}$ and a maximum Galactocentric radius ~ 20 kpc.

The integral γ -ray emissivity in the thin-target case can be easily estimated,

$$S(E_\gamma > 100 \text{ MeV}) \approx 6 \times 10^{-2} \text{ g}^{-1} \text{ s}^{-1}, \quad (1)$$

$$S(E_\gamma > 1 \text{ GeV}) \approx 5 \times 10^{-3} \text{ g}^{-1} \text{ s}^{-1}, \quad (2)$$

and the integral intensity simply following by multiplication with the column density, x , e.g., $I(E_\gamma > 1 \text{ GeV}) = xS(E_\gamma > 1 \text{ GeV}) \text{ cm}^{-2} \text{ s}^{-1}$, where x is in units of g cm $^{-2}$.

Any assumption of the spatial distribution of debris would be highly speculative. For an order of magnitude estimate we take the simplest case of debris concentrated in a spherical shell with radius d . In this case, the total mass of the debris is

$$M_d \sim 0.47d^2x M_\oplus, \quad (3)$$

where d is the distance in AU. It is enough to have $\sim 50 M_\oplus$ of material spread out over 4π at 10^3 AU, which corresponds

to 10^{-4} g cm $^{-2}$, to obtain a γ -ray albedo flux within an order of magnitude of the IGRB. This column density corresponds to $\sim 10^{-3}$ of the total column density along the line of sight through the Galactic disk. Since the d^2 dependence is very strong, much less material is required to produce the same albedo γ -ray flux at a smaller effective distance and vice versa.

5. DISCUSSION

The total mass and distribution of SSSBs smaller than cometary nuclei are highly uncertain, as is the spatial distribution of debris. However, simulations indicate that the number of comets and the total mass considerably increase toward the inner edge of the OC. It is entirely possible that $\sim 100 M_{\oplus}$ of debris is distributed in the vast space of the OC. Since the OC has spherical and disk components, it is possible that the OC γ -ray albedo is brighter around the ecliptic.

The minimal detectable mass in debris for other systems can also be estimated (Table 1). For example, assuming that KBOs are distributed uniformly within $\pm 10^\circ$ around the ecliptic, the fraction of the total solid angle subtended by the Kuiper Belt is $\Omega/4\pi = 0.173$. The detectable mass of KBO debris can then be calculated using Equation (3): $M_d = (\Omega/4\pi)0.47d^2x M_{\oplus} \sim 1.3 \times 10^{-2} M_{\oplus}$, with $x = 10^{-4}$ g cm $^{-2}$, and $d = 40$ AU.

Jovian and Neptunian Trojans would appear as point-like sources. The integral γ -ray flux from a point-like mass M_d of debris at a distance d AU is:

$$F(E_\gamma > 1 \text{ GeV}) = \frac{M_d S(E_\gamma > 1 \text{ GeV})}{4\pi d^2} \sim 0.01 \frac{M_{\oplus}}{d^2} \text{ cm}^{-2} \text{ s}^{-1}, \quad (4)$$

where we used the emissivity $S(E_\gamma > 1 \text{ GeV})$ corresponding to the interstellar CR spectrum calculated earlier. Since 1 GeV photons are produced by CR protons of $\gtrsim 10$ GeV, which are only slightly modulated in the heliosphere, this is a good approximation.

The one-year LAT integral point source sensitivity⁵ is $F_{1\text{yr}}(E_\gamma > 1 \text{ GeV}) \sim 1 \times 10^{-9}$ cm $^{-2}$ s $^{-1}$. This gives a detectability condition for one year of exposure:

$$M_d \gtrsim 1 \times 10^{-7} M_{\oplus} d^2. \quad (5)$$

The proposed method is sensitive enough to detect a debris mass as small as $\sim 0.1\% - 50\%$ of the total mass of the system. It is most sensitive for the MBA population due to its proximity, but can also provide meaningful limits on more distant populations, such as Jovian and Neptunian Trojans, KBOs, and the OC. A clear signature of the described process is the power-law spectrum of the γ -ray albedo ($\gtrsim 1$ GeV) which has an index similar to that of the incident CR spectrum. The larger photon statistics of the projected five-year LAT mission will probe even smaller debris masses for all these systems.

The sensitivity and resolution of the LAT will allow it to resolve many more individual sources, such as AGN, not resolved by EGRET and that contribute to current estimates of the IGRB. Other components of the remaining IGRB will therefore become more important. Understanding of the instrumental backgrounds within the LAT will allow discrimination of the IGRB at 10% of the current level (Atwood et al. 2009). This will allow a meaningful estimate of the foreground from the OC and other asteroid populations to be obtained. On the other hand, correct

determination of such a foreground will allow for more accurate determination of the truly extragalactic component of the diffuse emission.

I.V.M. and T.A.P. acknowledge support from a NASA Astronomy and Physics Research and Analysis (APRA) grant NNX09AC15G. T.A.P. acknowledges support from the US DOE.

REFERENCES

- Atwood, W. B., et al. 2009, *ApJ*, submitted
- Backman, D. E., Dasgupta, A., & Stencel, R. E. 1995, *ApJ*, **450**, L35
- Badhwar, G. D., Stephens, S. A., & Golden, R. L. 1977, *Phys. Rev. D*, **15**, 820
- Bignami, G. F., Fichtel, C. E., Hartman, R. C., & Thompson, D. J. 1979, *ApJ*, **323**, 649
- Brandt, J. C., & Chapman, R. D. 2004, *Introduction to Comets* (2nd ed.; Cambridge: Cambridge Univ. Press)
- Brown, M. E. 2001, *AJ*, **121**, 2804
- Casanova, S., Dingus, B. L., & Zhang, B. 2007, *ApJ*, **656**, 306
- Chiang, J., & Mukherjee, R. 1998, *ApJ*, **496**, 752
- Dermer, C. D. 1986a, *ApJ*, **307**, 47
- Dermer, C. D. 1986b, *A&A*, **157**, 223
- Dermer, C. D. 2007, in *AIP Conf. Proc.* 921, Proc. 1st GLAST Symposium, ed. S. Ritz, P. Michelson, & C. Meegan (New York: AIP), 190
- Dohnanyi, J. S. 1969, *J. Geophys. Res.*, **74**, 2531
- Dones, L., Weissman, P. R., Levison, H. F., & Duncan, M. J. 2004, in *Comets II*, ed. M. C. Festou, et al. (Tucson, AZ: Univ. of Arizona Press)
- Ensslin, T. A., Biermann, P. L., Kronberg, P. P., & Wu, X.-P. 1997, *ApJ*, **477**, 560
- Farley, K. A., et al. 1998, *Science*, **280**, 1250
- Fernández, J. A. 2005, *Comets. Nature, Dynamics, Origin, and their Cosmogenic Relevance* (Dordrecht: Springer)
- Grün, E. 2007, *Solar System Dust*, in *Encyclopedia of the Solar System*, ed. L. A. McFadden, P. R. Weissman, & T. V. Johnson (2nd ed.; New York: Elsevier), 621
- Hills, J. G. 1981, *AJ*, **86**, 1730
- Kamae, T., et al. 2006, *ApJ*, **647**, 692
- Kelner, S. R., Aharonian, F. A., & Bugayov, V. V. 2006, *Phys. Rev. D*, **74**, 034018
- Kronk, G. W. 1999, *Cometography: A catalog of comets. Vol. 1: Ancient to 1799* (New York: Cambridge Univ. Press)
- Levison, H. F., Dones, L., & Duncan, M. J. 2001, *AJ*, **121**, 2253
- Loeb, A., & Waxman, E. 2000, *Nature*, **405**, 156
- Luu, J.-X., & Jewitt, D. C. 2002, *ARA&A*, **40**, 63
- Marsden, B. G., & Williams, G. V. 2003, *Catalogue of Cometary Orbits 2003* (15th ed.; Cambridge: Smithsonian Astrophys. Obs.)
- Miniati, F. 2002, *MNRAS*, **337**, 199
- Morbidelli, A. 2005, arXiv:astro-ph/0512256
- Moskalenko, I. V., & Porter, T. A. 2007, *ApJ*, **670**, 1267
- Moskalenko, I. V., Porter, T. A., & Digel, S. W. 2006, *ApJ*, **652**, L65
- Moskalenko, I. V., & Strong, A. W. 1998, *ApJ*, **493**, 694
- Moskalenko, I. V., & Strong, A. W. 2000, *ApJ*, **528**, 357
- Moskalenko, I. V., et al. 2008, *ApJ*, **681**, 1708
- Mücke, A., & Pohl, M. 2000, *MNRAS*, **312**, 177
- Mukherjee, R., & Chiang, J. 1999, *Aph*, **11**, 213
- Oort, J. H. 1950, *Bull. Astron. Inst. Neth.*, **11**, 91
- Orlando, E., & Strong, A. W. 2007, *Ap&SS*, **309**, 359
- Orlando, E., & Strong, A. W. 2008, *A&A*, **480**, 847
- Orth, C. D., & Buffington, A. 1976, *ApJ*, **206**, 312
- Pavlidou, V., & Fields, B. D. 2002, *ApJ*, **575**, L5
- Sreekumar, P., et al. 1998, *ApJ*, **494**, 523
- Stecker, F., & Salamon, M. 1996, *ApJ*, **464**, 600
- Stecker, F. W. 1970, *Ap&SS*, **6**, 377
- Stephens, S. A., & Badhwar, G. D. 1981, *Ap&SS*, **76**, 213
- Strong, A. W., Moskalenko, I. V., & Reimer, O. 2004a, *ApJ*, **613**, 962
- Strong, A. W., Moskalenko, I. V., & Reimer, O. 2004b, *ApJ*, **613**, 956
- Thompson, D. J., Bertsch, D. L., Morris, D. J., & Mukherjee, R. 1997, *J. Geophys. Res. A*, **102**, 14735
- Thompson, D. J., & Fichtel, C. E. 1982, *A&A*, **109**, 352
- Weissman, P. R. 2000, *Oort Cloud*, in *Encyclopedia of Astronomy and Astrophysics*, ed. P. Murdin (London: Nature Publishing Group)

⁵ http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.