Local Flux of Low-Energy Antiprotons from Evaporating Primordial Black Holes

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We investigate low-energy cosmic-ray antiprotons ($\bar{p}$'s) arising from the fragmentation of quarks and gluons emitted from evaporating primordial black holes (PBHs). To calculate the local interstellar flux of these $\bar{p}$'s, their propagation in the Galaxy is described by a 3D Monte Carlo simulation based on the diffusion model. This flux is used with recent observations to derive new upper limits on (i) the local PBH explosion rate $\mathcal{R} < 1.7 \times 10^{-2}\ \mathrm{pc}^{-3}\,\mathrm{yr}^{-1}$, (ii) the fraction of the Universe's mass going into PBHs with particular mass, and (iii) the average density of PBHs in the Universe. [S0031-9007(96)00042-7]

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From a standpoint of cosmological understanding, it would be of great value to confirm the existence or nonexistence of primordial black holes (PBHs), which may have formed in the early Universe via initial density fluctuations, phase transitions, or the collapse of cosmic strings (for a review, see Ref. [1]). Hawking [2] first showed that black holes (BHs) emit particles and evaporate by quantum effects, noting that PBHs are the only ones with a mass small enough for the quantum emission rate to be significant, possibly yielding an observable effect. For example, the hard γ rays from small enough PBHs may contribute to the diffuse γ-ray background spectrum, though no distinct signature has been observed. Thus, this leads to an upper limit (U.L.) on the average density of PBHs in the Universe; i.e., the ratio of their density to the critical density of the Universe, Ω_{PBH}, must be $\lesssim 10^{-8}$ [3].

Despite such a stringent limit, their signature could still appear in the spectrum of cosmic-ray antiprotons ($\bar{p}$'s) [4], which are generally considered to be secondary products from interactions of cosmic-ray protons (p's) with the interstellar medium. This possibility arises because, although the kinematics of secondary $\bar{p}$ production by such p's should lead to a steep drop in the resultant $\bar{p}$ flux at kinetic energies less than 2 GeV, the expected flux of $\bar{p}$'s from PBHs (PBH-$\bar{p}$'s) has contrastingly been shown to increase with decreasing kinetic energy down to $\sim$0.2 GeV [4]; thus providing a distinct signature below 1 GeV. Hence, searches for such low-energy cosmic-ray $\bar{p}$'s could lead to a novel constraint on the density of PBHs, or more importantly, demonstrate their existence. With this in mind, and spurred by the recent detection of cosmic-ray $\bar{p}$'s with kinetic energies less than 0.5 GeV, being accomplished during a 13-h balloon flight (BESS '93) [5], we present a new method describing the propagation of $\bar{p}$'s in the Galaxy, thereby obtaining the most accurate-to-date spectrum of local interstellar PBH-$\bar{p}$ flux. We also use these results with observed data [5] to derive a new U.L. on the density of PBHs which are expiring near the solar system, after which we discuss its cosmological aspects assuming their formation via initial density fluctuations.

The source spectrum of PBH-$\bar{p}$'s is determined using general properties of BH evaporation [6,7]. Briefly, an uncharged, nonrotating BH with mass M emits particles with spin s and total energy between $(Q,\ Q + dQ)$ at a rate [2]

$$\frac{dN}{dt} = \frac{\Gamma_s dQ}{2\pi\hbar}\left[\exp\left(\frac{Q}{kT}\right) - (-1)^{2s}\right]^{-1} \tag{1}$$

per degree of particle freedom, where T is the BH temperature $[= \hbar c^3/8\pi GMk = 1.06 \times 10^{13}(M/\mathrm{g})^{-1}$ GeV, with $k = 1]$, and Γ_s is the dimensionless absorption probability for the emitted species. Considering all species, the corresponding mass loss rate can be expressed as [7]

$$\frac{dM}{dt} = -5.34 \times 10^{25} f(M)\left(\frac{M}{\mathrm{g}}\right)^{-2}\ \mathrm{g\,s}^{-1}, \tag{2}$$

where $f(M)$, a function of the number of emitted species, is normalized to unity for large M ($\gg 10^{17}$ g) and increases with decreasing M. From Eq. (2), it follows that $M_* \simeq 5.3 \times 10^{14}[t_u/(16\ \mathrm{Gyr})]^{1/3}$ g, or $3 \times 10^{-19}[t_u/(16\ \mathrm{Gyr})]^{1/3}$ in units of solar mass, where M_* is the initial mass of a PBH expiring today; i.e., its initial lifetime equals the present age of the Universe t_u, being taken here as 16 Gyr [8]. PBHs with initial mass $M_i < M_*$ should have completely evaporated by now, while those with M_i slightly larger than M_* have an extremely high present temperature and will soon expire by "explosion."

Under the assumptions that (i) Eq. (1) holds for each emitted species of quarks and gluons and (ii) all PBH-$\bar{p}$'s are their fragments, which is consistent with observed e^+e^- annihilations, we calculate the PBH-$\bar{p}$ source spectrum per unit volume via the following three-step procedure: (1) The JETSET 7.4 [9] Monte Carlo simulation code is used to obtain the fragmentation function $dg_{\bar{p}}^{(j)}(E_{\bar{p}}, Q)/dE_{\bar{p}}$ describing the fragmentation of each emitted species j with total energy Q into $\bar{p}$'s with total energy $E_{\bar{p}}$; (2) the $\bar{p}$ emission spectrum from a BH at present temperature T, $d\Phi_{\bar{p}}(E_{\bar{p}},T)/dE_{\bar{p}}$, is calculated by convolving Eq. (1) with $dg_{\bar{p}}^{(j)}(E_{\bar{p}},Q)/dE_{\bar{p}}$ for $Q \geq E_{\bar{p}}$ and summing over all j and their degrees of freedom; and (3) the expected PBH-$\bar{p}$ source spectrum per unit volume is obtained by convolving the PBH present temperature distribution dn/dT with $d\Phi_{\bar{p}}(E_{\bar{p}},T)/dE_{\bar{p}}$ for $T \gtrsim 0.1$ GeV, where n is the number of PBHs per unit volume. Under Eq. (2), dn/dT vs T ($\gtrsim$0.1 GeV) is roughly a power-law function ($\propto T^{-4.2}$), with its normalization being solely determined by the value of the initial mass spectrum dn/dM_i at $M_i = M_*$.

We checked the reliability of our use of JETSET 7.4 [9] via data from e^+e^- colliders, i.e., observed $\bar{p}$ spectra obtained from the fragmentation of quarks and gluons at various Q relevant to evaporating PBHs. First, we verified that the predominant contribution to PBH-$\bar{p}$'s occurs at $Q = 1$–5 GeV, after which the simulated $\bar{p}$ spectra from quark fragmentation were compared with DASP data at $Q = 1.8$–2.5 GeV [10] and ARGUS data at $Q = 4.99$ GeV [10], while those from gluon fragmentation with ARGUS data from the direct decay of $\Upsilon(1S)$, which mainly proceeds through three gluons with an average energy of $m_{\Upsilon(1S)}/3 = 3.2$ GeV [10]. Resultant comparisons showed good agreement (data not shown).

Since the propagation of PBH-$\bar{p}$'s in the Galaxy has thus far only been roughly treated [4], we calculate the local interstellar PBH-$\bar{p}$ flux from the PBH-$\bar{p}$ source spectrum utilizing a 3D Monte Carlo simulation code based on the diffusion model, an expansion of the 1D simulation by Owens and Jokipii [11]. We assume that the PBH spatial distribution is proportional to the mass density distribution within the galactic halo, i.e., $\propto [1 + (r/r_c)^2]^{-1}$ [12], where r is a distance from the galactic center and r_c is the core radius of 7.8 kpc. As shown later, the local PBH-$\bar{p}$ flux arises only from nearly expired PBHs existing within a few kpc away from the solar system, whose location is at $r = r_\odot = 8.5$ kpc. Accordingly, the local PBH-$\bar{p}$ flux can be calculated via the three-step procedure by simply using $dn(M_i = M_*, r = r_\odot)/dM_i$, which is parametrized by introducing an unknown parameter ε_*:

$$\frac{dn}{dM_i}(M_i = M_*, r = r_\odot) = \varepsilon_* \frac{\rho_{h\odot}}{M_*^2}, \tag{3}$$

where $\rho_{h\odot}$ is the local density of halo dark matter ($\simeq$0.3 GeV cm^{-3} [13]). Under Eq. (3), ε_* represents the ratio of the density of PBHs with $M_i = M_*$ to $\rho_{h\odot}$.

Details regarding the diffusive propagation of $\bar{p}$'s will be described elsewhere [14]. Briefly, however, each $\bar{p}$ ejected from the fragmentation of quarks and gluons is assigned to an initial position $\mathbf{x}_0$ and energy E_0, after which it travels $\mathbf{x}$ to $\mathbf{x} + \mathbf{u}\sqrt{6D\Delta t} + (\nabla D)\Delta t$ in each subsequent time step Δt, where $\mathbf{u}\sqrt{6D\Delta t}$ represents the effect of isotropic diffusion during Δt, $\mathbf{u}$ is a unit vector with random direction, $D = D(\mathbf{x})$ is the diffusion coefficient, and $(\nabla D)\Delta t$ expresses the anisotropy of diffusion caused by the spatial gradient of D. We do not consider the effect of convection due to galactic wind, because Webber, Lee, and Gupta [15] showed that it does not significantly affect cosmic-ray propagation. Regarding subsequent collisions and energy loss, the interstellar medium (ISM) is considered to consist of 90% hydrogen and 10% helium atoms [16], and its number density distribution is modeled as $n_{\text{atom}} = 1.1 \exp[-z/(100 \text{ pc})]$ atoms/cm^3, where z is the perpendicular distance from the galactic plane ($z = 0$). While propagating through the ISM, $\bar{p}$'s lose energy by ionization and are lost by annihilation. Those $\bar{p}$'s passing near the solar system ($\lesssim$25 pc) are included in the flux calculation.

The Galaxy is modeled as a cylindrical diffusing halo [15] with a diameter of 40 kpc and halo thickness of $2h$. Free escape is assumed to occur at the boundaries. As normally done, we parametrize the diffusion coefficient as $D = D_0(z)D_1(R)$, where R is the rigidity of the particle. We apply three halo models for $D_0(z)$ [Fig. 1(a) shows $D_0(z)^{-1}$]: two with constant D_0 but different values of h (models I and II), and one in which D_0 is dependent on z (model III). Assuming D_0 is constant, D_0/h and

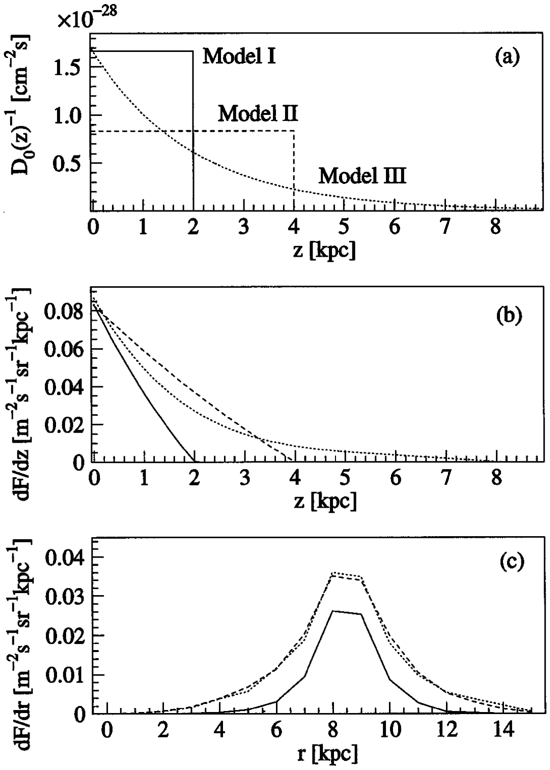

FIG. 1. (a) Distribution of $D_0(z)^{-1}$ in halo models I–III as shown in the z direction where the solar system is located on the galactic plane ($z = 0$). (b) Distribution of PBHs contributing to the local $\bar{p}$ flux F near the solar system, obtained by assuming $\varepsilon_* = 1.0 \times 10^{-8}$, as shown in the z direction. (c) The same as (b) shown in the r direction where the solar system is located at $r = 8.5$ kpc.

$D_1(R)$ are determined [15] as $(8 \pm 1.6) \times 10^5\ \mathrm{cm\,s^{-1}}$ and $\sim(R/\mathrm{GV})^{0.6}$, respectively, which fits the secondary to primary ratios of cosmic-ray nuclei, e.g., the ratios of boron to carbon (B/C) and subiron to iron (sub-Fe/Fe). The value of h is also constrained from 2 to 4 kpc [15] in order to fit the radioactive secondary to stable secondary ratios, e.g., the ratios of radioactive beryllium to stable beryllium ($^{10}\mathrm{Be}/^{9}\mathrm{Be}$). Thus, $h = 2$ and 4 kpc in models I and II, respectively. Model III also fits the above ratios at the same $D_1(R)$.

The simulated distribution of PBHs contributing to the integrated $\bar{p}$ flux F near the solar system, obtained by assuming $\varepsilon_* = 1.0 \times 10^{-8}$, is shown for halo models I–III in Figs. 1(b) and 1(c) in the z and r directions, respectively. Note that all models show the same contribution at $z = 0$ (galactic plane) as they are constrained to reproduce the observed secondary to primary ratios which originate from secondary production occurring there. In addition, only PBHs within a few kpc away from the solar system contribute a substantial flux. When considering these results along with the fact that the mass density within this region is relatively constrained [13], this indicates that the solar system $\bar{p}$ flux is only slightly dependent on the assumed mass density distribution within the Galactic halo [12]. The $\bar{p}$ mean confinement time is also calculated by the code as 4.0×10^7, 7.9×10^7, and 8.0×10^7 yr for models I–III, resulting in $F = 0.78 \times 10^{-1}$, 1.53×10^{-1}, and $1.55 \times 10^{-1}\ \mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$, respectively.

As we have shown that the local PBH-$\bar{p}$ flux can be due only to contributions from PBHs that are close to explosion and exist within a few kpc away from the solar system, data from searches in which low-energy cosmic-ray $\bar{p}$'s are detected can *directly* constrain (or possibly reveal) the PBH explosion rate averaged over this local region, termed here as the local PBH explosion rate $\mathcal{R}$, i.e.,

$$\begin{aligned} \mathcal{R} &\equiv \frac{dn}{d\tau_i}(\tau_i = t_u,\, r = r_\odot) \\ &= \frac{dn}{dM_i}(M_i = M_*,\, r = r_\odot)\,\frac{M_*}{3t_u}\,, \end{aligned} \tag{4}$$

where τ_i $[= t_u(M_i/M_*)^3$ at $M_i \approx M_*]$ is the initial lifetime of PBHs with initial mass M_i. Figure 2(a) shows simulated local interstellar PBH-$\bar{p}$ flux using model III with two possible values of $\mathcal{R}$, i.e., 1×10^{-2} and $1 \times 10^{-3}\ \mathrm{pc^{-3}\,yr^{-1}}$. Then, to compare this $\bar{p}$ flux with observational data, we converted it into the $\bar{p}/p$ ratio at the top of the atmosphere (TOA) by assuming that (i) the interstellar p flux $J_p = 1.5 \times 10^4 \beta^{-1}(R/\mathrm{GV})^{-2.74}\ \mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}}$ [17], where β is the ratio of particle velocity to the velocity of light, and (ii) the corresponding flux of both p's and $\bar{p}$'s at TOA can be similarly calculated by accounting for solar modulation using the force-field approximation [18] with modulation parameter $\phi = 650$ MV, which corresponds to that obtained from the BESS '93 flight [5]. Figure 2(b) compares the resultant $\bar{p}/p$ ratio for PBH-$\bar{p}$'s with the expected $\bar{p}/p$ ratio for secondary $\bar{p}$'s [14] and observational data [5,19–23]. Note that no distinct signature of evaporating PBHs is apparent; i.e., at kinetic energies below 1 GeV, the data show no tendency to reach a constant $\bar{p}/p$ ratio. As no signature exists, statistical analysis of recent observations [5] leads to the following U.L. on $\mathcal{R}$ with 90% confidence level (C.L.):

$$\mathcal{R} < 1.7 \times 10^{-2}\ \mathrm{pc^{-3}\,yr^{-1}}, \tag{5}$$

which is almost 8 orders of magnitude more stringent than the present U.L. on the rate of 50-TeV γ-ray bursts ($\mathcal{R} < 8.5 \times 10^5\ \mathrm{pc^{-3}\,yr^{-1}}$ [24]), and the practical sensitivity for 100-MeV γ-ray bursts ($\mathcal{R} \sim 10^6\ \mathrm{pc^{-3}\,yr^{-1}}$ [25]). Note that, although the observed diffuse γ-ray background spectrum places an upper limit on the average density of PBHs in the Universe, it cannot be used to set a direct limit on the local $\mathcal{R}$ because of the uncertainties on PBH clustering [3].

Equations (3)–(5) give the following U.L. on ε_* with 90% C.L.:

$$\varepsilon_* < 2.8 \times 10^{-8}\left(\frac{\rho_{h\odot}}{0.3\ \mathrm{GeV\,cm^{-3}}}\right)^{-1}\left(\frac{t_u}{16\ \mathrm{Gyr}}\right)^{4/3}, \tag{6}$$

which can be used to derive an U.L. on the fraction of the Universe's mass going into PBHs with mass M_*,

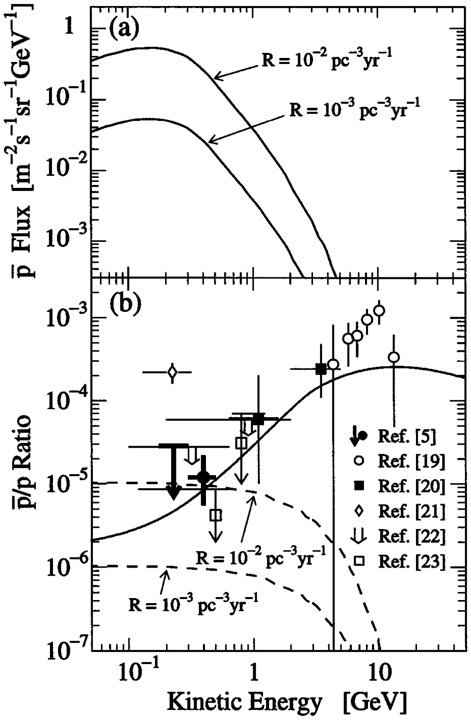

FIG. 2. (a) Simulated local interstellar PBH-$\bar{p}$ flux using model III with $\mathcal{R} = 1 \times 10^{-2}$ and $1 \times 10^{-3}\ \mathrm{pc^{-3}\,yr^{-1}}$. (b) Corresponding $\bar{p}/p$ ratio for PBH-$\bar{p}$'s at the top of the atmosphere (dashed lines), the expected $\bar{p}/p$ ratio for secondary $\bar{p}$'s (solid line) [14], and observational data [5,19–23].

i.e., $\beta(M_*)$ [1]. If PBHs are assumed to have formed via initial density fluctuations, $\beta(M_*)$ should be closely related to their amplitude on a scale of M_*. Thus, under this assumption, and for a flat Friedmann universe, Eq. (3) gives $\beta(M_*) \sim 1 \times 10^{-18}\varepsilon_*(\Omega_h/0.1)$, where Ω_h is the ratio of the density of halo dark matter to the critical density of the Universe. Finally, assuming $\Omega_h = 0.1$ [8], Eq. (6) leads to an U.L. of $\beta(M_*) < 3 \times 10^{-26}$.

Further, by assuming that such initial density fluctuations are scale invariant, the initial mass spectrum of PBHs should have a power-law form, i.e., $dn/dM_i \propto M_i^{-\alpha}$ [1], where $\alpha = 5/2$ if the Universe was radiation dominated when PBHs formed. Using this initial mass spectrum normalized by Eq. (3) at $M_i = M_*$, we integrate $M_i dn/dM_i$ over $M_* \leq M_i \leq \infty$ to obtain $\Omega_{\mathrm{PBH}} \equiv \varepsilon_*\Omega_h \int_1^\infty x^{1-\alpha}\,dx = 2 \times 10^{-1}\varepsilon_*(\Omega_h/0.1)$, where $x \equiv M_i/M_*$. Finally, assuming $\Omega_h = 0.1$ [8], Eq. (6) leads to an U.L. of $\Omega_{\mathrm{PBH}} < 6 \times 10^{-9}$, being comparable to that from the diffuse γ-ray background spectrum ($\lesssim 10^{-8}$) [3].

In closing, if future long-duration ($\sim$8 days) balloon flights allow us to precisely measure the cosmic-ray $\bar{p}$ flux at kinetic energies from 0.2 to 2 GeV, the U.L. on $\mathcal{R}$ can be significantly reduced to $\sim 2 \times 10^{-3}$ pc^{-3} yr^{-1}, or more importantly, such observations could confirm the existence of evaporating PBHs.

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[1] B. J. Carr, in *Observational and Theoretical Aspects of Relativistic Astrophysics and Cosmology,* edited by J. L. Sanz and L. J. Goicoechea (World Scientific, Singapore, 1985), p. 1.

[2] S. W. Hawking, Commun. Math. Phys. **43**, 199 (1975).

[3] D. N. Page and S. W. Hawking, Astrophys. J. **206**, 1 (1976); F. Halzen, E. Zas, J. H. MacGibbon, and T. C. Weekes, Nature (London) **353**, 807 (1991).

[4] P. Kiraly *et al.*, Nature (London) **293**, 120 (1981); M. S. Turner, *ibid.* **297**, 379 (1982); J. H. MacGibbon and B. J. Carr, Astrophys. J. **371**, 447 (1991).

[5] K. Yoshimura *et al.*, Phys. Rev. Lett. **75**, 3792 (1995).

[6] J. H. MacGibbon and B. R. Webber, Phys. Rev. D **41**, 3052 (1990).

[7] J. H. MacGibbon, Phys. Rev. D **44**, 376 (1991).

[8] E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, New York, 1990).

[9] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).

[10] DASP Collaboration, R. Brandelik *et al.*, Nucl. Phys. **B148**, 189 (1979); ARGUS Collaboration, H. Albrecht *et al.*, Z. Phys. C **44**, 547 (1989).

[11] A. J. Owens and J. R. Jokipii, Astrophys. J. **215**, 677 (1977); **215**, 685 (1977).

[12] J. A. R. Caldwell and J. P. Ostriker, Astrophys. J. **251**, 61 (1981).

[13] R. A. Flores, Phys. Lett. B **215**, 73 (1988).

[14] T. Mitsui (to be published).

[15] W. R. Webber, M. A. Lee, and M. Gupta, Astrophys. J. **390**, 96 (1992).

[16] J. J. Engelmann *et al.*, Astron. Astrophys. **233**, 96 (1990).

[17] E. S. Seo *et al.*, Astrophys. J. **378**, 763 (1991).

[18] L. J. Gleeson and W. I. Axford, Astrophys. J. **154**, 1011 (1968).

[19] R. L. Golden *et al.*, Phys. Rev. Lett. **43**, 1196 (1979); Astrophys. Lett. **24**, 75 (1984).

[20] E. A. Bogomolov *et al.*, in *Proceedings of the Twentieth International Cosmic Ray Conference, Moscow, 1987,* edited by V. A. Kozyarivsky *et al.*, (Nauka, Moscow, 1987), Vol. 2, p. 72; in *Proceedings of the Twenty-First International Cosmic Ray Conference, Adelaide, 1989,* edited by R. J. Protheroe (Graphic Services, Northfield, South Australia, 1990), Vol. 3, p. 288.

[21] A. Buffington, S. M. Schindler, and C. R. Pennypacker, Astrophys. J. **248**, 1179 (1981).

[22] S. P. Ahlen *et al.*, Phys. Rev. Lett. **61**, 145 (1988); M. H. Salamon *et al.*, Astrophys. J. **349**, 78 (1990).

[23] R. E. Streitmatter *et al.*, in *Proceedings of the Twenty-First International Cosmic-Ray Conference* (Ref. [20]), Vol. 3, p. 277; A. Moats *et al.*, *ibid.* **3**, 284 (1990); S. J. Stochaj, Ph.D thesis, University of Maryland (1990).

[24] D. E. Alexandreas *et al.*, Phys. Rev. Lett. **71**, 2524 (1993).

[25] D. V. Semikov, Astrophys. J. **436**, 254 (1994).