# Life Extinctions by Cosmic Ray Jets

Arnon Dar, Ari Laor, and Nir J. Shaviv
*Department of Physics and Space Research Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel*

(Received 16 May 1997)

High energy cosmic ray jets from nearby mergers or accretion induced collapse of neutron stars that hit the atmosphere can produce lethal fluxes of atmospheric muons at ground level, underground and underwater, destroy the ozone layer, and radioactivate the environment. They could have caused some of the massive life extinctions on planet Earth in the past 570 Myr. Biological mutations due to such ionizing radiations could have caused the fast appearance of new species after these mass extinctions. [S0031-9007(98)06474-6]

PACS numbers: 87.50.Gi, 97.60.Jd, 98.70.Sa

The early history of life during the Precambrian until its end 570 Myr ago is poorly known. Since then the diversity of both marine and continental life has increased exponentially. Analysis of fossil records shows that this diversification was interrupted by five massive extinctions and some smaller extinction peaks [1]. The largest extinction occurred about 251 Myr ago at the end of the Permian period. The global species extinction ranged then between 80% to 95%, much more than, for instance, the end-Ordovician extinction 439 Myr ago which eliminated ~57% of marine genera, or the Cretaceous-Tertiary extinction 64 Myr ago which killed the dinosaurs and claimed ~47% of existing genera [2]. In spite of intensive studies it is still not known what caused the mass extinctions, how quick were they, and whether they were subject to regional variations. Many extinction mechanisms have been proposed but no single mechanism seems to provide a satisfactory explanation of both the marine and continental extinction levels, the biological extinction patterns, and the repetition rate of mass extinctions [1,2]. These include astrophysical mechanisms, such as meteoritic impact that explains the iridium anomaly which was found at the Cretaceous/Tertiary boundary [3] but has not been found in all the other extinctions [4], supernova explosions [5], and gamma rays from bursts [6] which do not occur close enough and at a sufficiently high rate to explain the observed rate of mass extinctions.

In this Letter we propose that high energy cosmic ray jets (CRJs) from nearby mergers or accretion induced collapse (AIC) of neutron stars (NS) that hit the atmosphere, produced lethal fluxes of atmospheric muons at ground level, underground and underwater, destroyed the ozone layer, and radioactivated the environment. Nearby NS mergers and AIC could explain the massive extinction on the ground, underground and underwater, and the higher survival levels of radiation resistant species and terrain sheltered species in the five "great" life extinctions on planet Earth in the past 570 Myr. More distant Galactic mergers and AIC could have caused smaller extinctions. Biological mutations due to ionizing radiations may explain the fast appearance of new species after massive extinctions.

Intense cosmic ray bursts enrich rock layers with detectable traces of cosmogenically produced radioactive nucleides such as $^{129}$I, $^{146}$Sm, $^{205}$Pb, and $^{244}$Pu. Tracks of high energy particles in rock layers on Earth and on the moon may also contain records of intense cosmic irradiations. An early warning of future extinctions due to NS mergers and AIC can be obtained by identifying, mapping, and timing all the nearby binary NS systems. A final warning of an approaching CRJ from a nearby NS merger and AIC would be provided by an enormous gamma ray burst (GRB) from the same direction a few days before the arrival of the CRJ.

Recent observations of optical afterglows of GRBs confirm [7] previous indications that GRBs are at cosmological distances [8]. Cosmological distances ($D \sim 10^{28}$ cm) imply an enormous release of energy in gamma rays in a very short time. Such an energy release takes place in a merger and AIC of NS where $\sim M_{\odot}c^2 \approx 2 \times 10^{54}$ erg gravitational binding energy is released in a few milliseconds in the form of gravitational waves, neutrinos, and kinetic energy of relativistic ejecta. Therefore, a merger and AIC of NS have been suggested long ago [9] as the origin of cosmological GRBs. Other features of GRBs (rates, time variability, and durations) also suggest a NS merger and AIC origin although the exact mechanism which converts a significant fraction of their energy release into gamma rays is still not clear [8].

Merger and AIC of NS in close binaries, probably, proceed through the formation of an accretion disk due to strong gravitational tidal forces. Observations seem to indicate that highly collimated jets are ejected by all systems where matter is undergoing disk accretion onto a compact central object. They also indicate that the jet kinetic energy is a considerable fraction of the accretion power and that the jets reach large distances: Highly collimated relativistic jets from active Galactic nuclei (AGN), which are believed to be powered by mass accretion onto a massive black hole at a typical rate of $\sim M_{\odot}$ yr$^{-1}$, reach distances up to a million light years before disruption [10].

Highly collimated relativistic matter that is ejected sporadically by microquasars (superluminal Galactic sources such as GRS 1915+105 [11] and GRO J165-40 [12]) and by x-ray sources (such as SS433 [13] and Cygnus X-3 [14]), which are close binary systems where mass is accreted onto a neutron star or a stellar black hole from a companion star, seem to reach hundreds of light years before disruption. The exact mechanism by which the gravitational and electromagnetic fields around accreting and rotating compact objects produce the highly collimated relativistic jets is still unknown. However, the final accretion rates ($\gg M_\odot\ \mathrm{s}^{-1}$) and magnetic fields of NS undergoing merger and AIC in a close binary system are probably many orders of magnitude larger than those in AGN. Therefore, it is natural to expect that highly collimated relativistic jets are also ejected in mergers and AIC of NS, that they produce the cosmological gamma ray bursts [15] by internal interactions and/or through interaction with the external medium [16], and they reach distances of $D \sim 1$ kpc before disruption. In fact, if the optical and radio afterglows from GRBs which last for $T \sim$ months are formed by jets which point towards the observer then these jets must reach distances of $\sim c\Gamma^2 T \geq 10^3$ light years for $\Gamma \geq 100$. After disruption the jet particles are isotropized by the Galactic magnetic field and form the Galactic cosmic rays. Here we show that if these jets hit an Earth-like planet before disruption, they can devastate all forms of life on it.

In view of the uncertainties in modeling jet ejection in NS merger and AIC, rather than relying on numerical simulations (no fully relativistic three dimensional numerical calculations of NS merger and AIC are available yet) we have assumed [15] that these jets produce GRBs and inferred their properties from the observed properties of GRBs [8]: In order to explain GRBs the ejected jets must have typical Lorentz factors of $\Gamma \sim 10^3$, beaming angles $\Delta\Omega \leq 1/100$ similar to those observed/estimated for AGN and microquasars, and ejected mass $\Delta M \sim (dM/d\Omega)\Delta\Omega \leq 10^{-4} M_\odot$ (i.e., released kinetic energy bounded by $E_K = \Gamma \Delta M c^2 \ll M_\odot c^2 \sim 2 \times 10^{54}$ erg).

Undisrupted jets from NS-NS mergers can be devastating to life on nearby planets: At a distance of 1 kpc their duration is $\delta t \sim D/2c\Gamma^2 \sim 1$ day$-$2 months for typical values of $\Gamma$ between 1000 and 100, respectively. The time integrated energy flux of the jet at $D \sim 1$ kpc is, typically, $\sim 10^{12}$ Tev cm$^{-2}$. Thus, the energy deposition in the atmosphere by the jet is equivalent to the total energy deposition of Galactic cosmic rays in the atmosphere over $\sim 10^7$ yr. However, the typical energy of the cosmic rays in the CRJ is $\sim 1$ TeV per nucleon, compared with $\sim 1$ GeV per nucleon for ordinary cosmic ray nuclei. Collisions of such particles in the atmosphere generate atmospheric cascades where a significant fraction of the CRJ energy is converted into "atmospheric muons" through leptonic decay modes of the produced mesons. Most of these muons do not decay in the atmosphere because of their high energy. The average number of high energy muons produced by nucleons of primary energy $E_p$, which do not decay in the atmosphere and reach sea level with energy $>E_\mu$ at zenith angle $\theta < \pi/2$, is given approximately by [17]

$$\langle N_\mu \rangle \sim (0.0145 E_p[\mathrm{TeV}])\,(E_p/E_\mu)^{0.757} \times (1 - E_\mu/E_p)^{5.25}/\cos\theta\,. \tag{1}$$

Thus a jet with energy of about 1 TeV per nucleon at a distance of 1 kpc produces at sea level a flux of atmospheric muons of

$$I_\mu(>3\ \mathrm{GeV}) \sim 10^{12}\ \mathrm{cm}^{-2}. \tag{2}$$

Such muons deposit energy in matter via ionization. Their energy deposition rate is [18] $\sim 2$ MeV g$^{-1}$ cm$^{-1}$. The whole-body lethal dose from penetrating ionizing radiation resulting in 50% mortality of human beings in 30 days [18] is $\approx 300$ rad $= 3 \times 10^4$ erg g$^{-1}$. Such a lethal dose is deposited by a muon burst of $I_\mu \sim 10^{10}$ cm$^{-2}$. The lethal dosages for other vertebrates can be a few times larger while for insects they can be as much as a factor 20$-$100 larger. Hence, a CRJ at $D \leq 1$ kpc produces a highly lethal burst of atmospheric muons. Because of muon penetration, the flux is lethal for most species even deep underwater (hundreds of meters) and underground, if the cosmic rays arrive from well above the horizon.

Although half of the planet is in the shade of the CRJ, planet rotation exposes a larger fraction of its surface to the CRJ and increases the CRJ lethality by the following:

(a) Pollution of the environment by radioactive nuclei, produced by spallation of atmospheric and surface nuclei by shower particles. Using the analytical methods of [19], we estimate that for an Earth-like atmosphere, the flux of energetic nucleons which reaches the surface is also considerable, $I_p(>100\ \mathrm{MeV}) \sim I_n(>100\ \mathrm{MeV}) \sim 10^{10}$ cm$^{-2}$. Global winds spread radioactive gases in a relatively short time over the whole planet.

(b) Depletion of stratospheric ozone by the reaction of ozone with nitric oxide, generated by the cosmic ray produced electrons in the atmosphere (massive destruction of stratospheric ozone has been observed during large solar flares which produced energetic protons [20]).

(c) Extensive damage to the food chain by radioactive pollution and massive extinction of vegetation and living organisms by ionizing radiations (the lethal radiation dosages for trees and plants are slightly higher than those for animals but still less than the flux given by Eq. (2) for all except the most resilient species).

The biological extinction pattern due to a CRJ depends on the exposure and the vulnerability of the different species to the primary and secondary effects of the CRJ. The exposure depends on the intensity and duration of the CRJ, on its direction relative to the rotation axis of Earth (Earth shadowing), on the local sheltering provided by terrain (canyons, mountains) and by underwater and underground habitats, and on the risk sensing/assessment and mobility of the various species. The lethality of the CRJ depends as well on the vulnerability of the various living species and vegetation to the primary ionizing radiation, to the drastic changes in the environment (e.g., radioactive pollution and destruction of the ozone layer), and to the massive damage and radioactive poisoning of the food chain. Although the exact biological signature may be quite complicated, and somewhat obscured in fossil records (due to poor or limited sampling, deterioration of the rocks with time, and dating and interpretation uncertainties because of bioturbational smearing) it may show the general pattern expected from a CRJ extinction. Indeed, a first examination of the fossil records suggests that there may be such a correlation between the extinction pattern of different species, their vulnerability to ionizing radiation, and the sheltering provided by their habitats and the environment they live in. For instance, insect species, which are less vulnerable to radiation, became extinct only in the greatest extinction—the end-Permian extinction 251 Myr ago. Even then, only 8 out of 27 orders were extinct compared with a global species extinction that ranged between 80% to 95% [4]. Also plants which are less vulnerable to ionizing radiation suffered a lower level extinction. Terrain, underground, and underwater sheltering may explain why certain families on land and in deep waters were not extinct even in the great extinctions, while most of the species in shallow waters and on the surface were extinct [4]. Mountain shadowing, canyons, caves, underground habitats, deep underwater habitats, and high mobility may also explain why various species like crocodiles, turtles, frogs (and most freshwater vertebrates), snakes, deep sea organisms, and birds did not become extinct. In particular, fresh underground waters in rivers and lakes are less polluted with radioisotopes and poisons produced by the CRJ than sea waters and may explain the survival of freshwater amphibians. Although the proposed mechanism cannot explain the enrichment of the K/T boundary layer by about $3 \times 10^5$ tons of iridium [3], it may explain most of the other mass extinctions where no iridium anomaly has been found.

Four NS-NS binaries have been observed in the Galactic disk [21] and one [22] in the globular cluster M1. They have been used to estimate that the NS-NS merger rate in the Milky Way (MW) is [23] $R_{\mathrm{MW}} \sim 10^{-4}\ \mathrm{yr}^{-1}$. It yields updated values in the range of $10^5$–$10^6\ \mathrm{yr}^{-1}$ mergers per Universe instead of [24] $\sim 10^3$–$10^4\ \mathrm{yr}^{-1}$. Therefore, if GRBs are produced by merger and AIC, they must be beamed into a solid angle $\Delta\Omega/4\pi \sim 10^{-2}$–$10^{-3}$ in order to yield a GRB observed rate [8] of $\sim 10^3\ \mathrm{yr}^{-1}$. The updated estimate of the NS-NS merger rate in the MW is also consistent with the estimated injection rate of cosmic rays in the MW: The escape rate of cosmic rays from the MW requires an average injection rate of $Q_{CR} \sim 10^{41}\ \mathrm{erg\,s}^{-1}$ in high energy cosmic rays in order to maintain a constant energy density of cosmic rays in the MW [25]. It can be supplied by jets from mergers and AIC if the kinetic energy of the jets is $E_K \sim 10^{52}$ erg and the NS-NS merger rate in the MW is $R_{\mathrm{MW}} \sim 3 \times 10^{-4}\ \mathrm{yr}^{-1}$.

Assuming that the spatial distribution of NS binaries and NS mergers in the MW follow the distribution of single pulsars [23],

$$dN \propto e^{-R^2/2R_0^2} e^{-|z|/h} R dR dz \,, \tag{3}$$

with a disk scale length, $R_0 \sim 4.8$ kpc, and a scale height, $h > 0.5$ kpc perpendicular to the disk and independent of disk position, we find that the average rate of CRJs from NS-NS mergers that reach planet Earth from distances $\leq 1$ kpc is $\sim 10^{-8}\ \mathrm{yr}^{-1}$. It is consistent with the five big extinctions which have occurred during the last 570 Myr. The relative strengths of these extinctions may reflect mainly different distances from the CRJ source. Beyond $\sim 1$ kpc from the explosion the angular spread and deceleration of the CRJ suppress its lethality. Such CRJs, if not too far, can still cause partial extinctions at a higher rate and induce biological mutations which may lead to the appearance of new species.

A CRJ could have enhanced the abundance of stable cosmogenic isotopes in the geological layer corresponding to the CRJ event, but, the enrichment may be negligible compared to their accumulation through long terrestrial exposure of the geological layers to Galactic cosmic rays prior to the CRJ. However, CRJ enrichment of sediments with unstable radioisotopes of mean lifetimes much shorter than the age of the solar system, $\tau \ll 4570$ Myr, but comparable to the extinction times, may be detectable through low traces mass spectrometry. In particular, fission of long lived terrestrial nuclei, such as $^{238}$U and $^{232}$Th, by shower particles, and capture of shower particles by such nuclei, may lead to terrestrial production of, e.g., $^{129}$I with $\tau = 15$ Myr, $^{146}$Sm with $\tau = 146$ Myr, $^{205}$Pb with $\tau = 43$ Myr, and $^{244}$Pu with $\tau = 118$ Myr, respectively. These radioisotopes may have been buried in underwater sediments and underground rocks which were protected from further exposure to cosmic rays. The main background to such a CRJ signature is the continuous deposition by cosmic rays and by meteoritic impacts on land and sea. Cosmic rays may include these trace radioisotopes due to nearby sources (e.g., SN explosions [5]) and because of spallation of stable cosmic ray nuclei in collisions with interstellar gas. Meteorites may include these trace elements due to a long exposure in space to cosmic rays. Finally, enhancement of the density of cosmic ray tracks in mica coincident with extinctions may also provide evidence for CRJ extinctions.

In conclusion, cosmic ray bursts from NS mergers and AIC may have caused massive life extinctions which interrupted the diversification of life on our planet. Their rate is consistent with the observed rate of mass extinctions in the past 570 Myr. They may be able to explain the complicated biological and geographical extinction patterns. Biological mutations induced by the ionizing radiations which are produced by the CRJs may explain the appearance of completely new species after extinctions. The iridium enrichment around the Cretaceous/Tertiary extinction that claimed the life of the dinosaurs cannot be due to a CRJ and may have been caused instead by a meteoritic impact. Isotopic anomaly signatures of CRJ extinctions may be present in the geological layers which recorded the extinctions. Elaborate investigations of the effects of CRJs from relatively nearby NS mergers and AIC and their biological, radiological, and geological fingerprints are needed before reaching a firm conclusion whether or not massive extinctions on planet Earth were caused by CRJs from NS mergers and AIC. An early warning of future extinctions due to mergers and AIC of compact stars can be obtained by identifying, mapping, and timing a compact star in binary systems. A final warning for an approaching CRJ from a nearby NS merger and AIC may be provided a few days before its arrival by its intense gamma ray emission.

[1] M.J. Benton, Science **278**, 52 (1995), and references therein.

[2] D.H. Erwin, Sci. Am. **275**, No. 1, 72 (1996), and references therein.

[3] L.W. Alvarez *et al.,* Science **208**, 1095 (1980).

[4] D.H. Erwin, Nature (London) **367**, 231 (1994), and references therein.

[5] M.A. Ruderman, Science **184**, 1079 (1974); J. Ellis and D. Schramm, Proc. Natl. Acad. Sci. U.S.A. **92**, 235 (1995); J. Ellis *et al.,* Astrophys. J. **470**, 1227 (1996); J.I. Collar, Phys. Rev. Lett. **76**, 999 (1996).

[6] S.E. Thorsett, Astrophys. J. **444**, L53 (1995).

[7] J. van Paradijs *et al.,* Nature (London) **386**, 686 (1997); K.C. Sahu *et al.,* Nature (London) **387**, 476 (1997); M.R. Metzger *et al.,* Nature (London) **387**, 878 (1997).

[8] See, e.g., C.A.A. Meegan *et al.,* Nature (London) **355**, 143 (1992). For recent reviews of GRBs see, e.g., G.J. Fishman and C.A.A. Meegan, Annu. Rev. Astron. Astrophys. **33**, 415 (1995); G.J. Fishman and D.H. Hartman, Sci. Am. **277**, No. 1, 34–39 (1997).

[9] B. Paczynski, Astrophys. J. **308**, L43 (1986); J. Goodman, A. Dar, and S. Nussinov, Astrophys. J. **314**, L7 (1987).

[10] See, e.g., C.M. Urry and P. Padovani, Astron. Soc. Pac. **107**, 803 (1995), and references therein.

[11] I.F. Mirabel and L.F. Rodriguez, Nature (London) **371**, 46 (1994).

[12] S.J. Tingay *et al.,* Nature (London) **374**, 141 (1995).

[13] See, e.g., B. Margon, Annu. Rev. Astron. Astrophys. **22**, 57 (1988).

[14] R.G. Strom *et al.,* Nature (London) **337**, 234 (1989).

[15] N.J. Shaviv and A. Dar, Astrophys. J. **447**, 863 (1995); N.J. Shaviv and A. Dar, astro-ph 9606032; A. Dar, Astrophys. J. Lett. astro-ph/9709231 (to be published).

[16] See, e.g., M.J. Rees and P. Meszaros, Mon. Not. R. Astron. Soc. **258**, 41 (1992).

[17] J.W. Elbert, *Proceedings of the 1978 DUMAND Summer Workshop*, edited by A. Roberts (DUMAND, La Jolla, 1979) Vol. 2, p. 101.

[18] R.M. Barnett *et al.,* Phys. Rev. D **54**, 1 (1996).

[19] A. Dar, Phys. Rev. Lett. **51**, 227 (1983).

[20] J.A.E. Stephenson *et al.,* Nature (London) **352**, 137 (1991).

[21] R.A. Hulse and J. Taylor, Astrophys. J. **195**, L51 (1975); G.H. Stokes *et al.,* Astrophys. J. **294**, L21 (1991); A. Wolszcan, Nature (London) **350**, 688 (1991).

[22] S.B. Anderson *et al.,* Nature (London) **346**, 42 (1990).

[23] See, e.g., E.P.J. van den Heuvel and D.R. Lorimer, Mon. Not. R. Astron. Soc. **283**, L37 (1996); S.F. Portegies Zwart and H.N. Spreeuw, Astron. Astrophys. **312**, 670 (1996); V.M. Lipunov *et al.,* Rev. Astrophys. Space Sci. **9**, 1–160 (1997); V.M. Lipunov *et al.,* Mon. Not. R. Astron. Soc. **288**, 245 (1997).

[24] E.S. Phinney, Astrophys. J. **380**, L17 (1991); R. Narayan, T. Piran, and I. Shemi, Astrophys. J. **379**, L17 (1991); S.J. Curran and D.L. Lorimer, Mon. Not. R. Astron. Soc. **276**, 347 (1995). See, however, L.V. Tutukov and A.R. Yungelston, Mon. Not. R. Astron. Soc. **260**, 675 (1993); V.M. Lipunov *et al.,* Astrophys. J. **454**, 493 (1995).

[25] L.O'C. Drury, F.A. Aharonian, and H.J. Volk, Astron. Astrophys. **287**, 959 (1994).