Astrophysical and Biological Implications of Gamma Ray Burst Properties

John Scalo and J. Craig Wheeler

The University of Texas at Austin

Received ______________________; accepted ______________________

ABSTRACT

Combining results from Schmidt (1999) for the local cosmic rate and mean peak luminosity of γ-ray bursts (GRBs) with recent work on the history of the cosmic star formation rate, we provide estimates for the local GRB rate per unit blue luminosity in galaxies. These values are used to examine a number of phenomena with the following conclusions: 1) The ratio of supernova rate to GRB rate is so large that it is difficult to maintain that more than a small fraction of neutron star or black hole-forming events produced GRBs, even allowing for generous collimation; 2) The GRB rate is so small that it is impossible to use these events to account for the majority of large HI holes observed in our own and other galaxies; the expected number of holes is much smaller than observed; 3) Modeling the GRB events in the Milky Way as a spatial Poisson process and allowing for modest enhancement in the star formation rate due to birth in a spiral arm, we find that the probability that the solar system was exposed to a fluence large enough to melt the chondrules during the first 10^7 yr of solar system history is negligibly small, especially considering that there is strong evidence that the chondrules were melted more than once; 4) We calculate the probability that the Earth's surface has been subjected to irradiation from GRBs at fluence levels exceeding those required for DNA alterations in most organisms during a given period of time. We account for downscattering through the atmosphere, which should result in about 1 percent of the near-Earth energy reaching the surface in the form of X-rays with energy around 20 keV. During the past 4.6 x 10^9 yr the Earth's surface should have been exposed to biologically significant short-lived jolts of X-rays about 500 times.

1. Introduction

The discovery of large redshifts for some γ-ray bursts (GRBs), through redshifts of afterglow lines or association with galaxies, showed that the intrinsic gamma ray luminosities must be very large. A succinct recent summary is given by van Paradijs (1999). These large photon energies, and the implied large associated kinetic energies, have led several workers to suggest that GRBs might be responsible for a number of observed astrophysical phenomena. These include the production of numerous large HI holes observed in our own and other galaxies (Efremov, Elmegreen & Hodge 1998, Loeb & Perna 1998) and the melting of dust grains resulting in the formation of chondrules in the early solar system (McBreen & Hanlon 1999). These issues depend sensitively on the assumed luminosities or kinetic energies of GRBs and especially their rates. Estimates of these quantities are possible because of the mounting evidence that GRBs are associated with massive star precursors. This is suggested by the presence of GRBs near the centers of galaxies with active star formation (Hogg & Fruchter 1999) and especially the recent light curve signatures detected in afterglow observations of GRB 980326 (Bloom et al. 1999) and GRB 970228 (Reichart 1999, Galama et al. 1999) that are consistent with supernovae (SN), as well as the earlier coincidence between GRB 980425 and SN 1998bw (Galama et al. 1998). For this reason it is believed that GRBs (at least those of long duration) track the star formation rate (SFR) in galaxies. Some assumptions about the average cosmic SFR history of the Universe as a function of redshift then allow a comparison of models with number-flux counts and other statistical constraints in order to derive average peak luminosities and rates.

Earlier work used GRB rates derived by assuming that all GRBs have the same luminosity (the standard candle assumption), as in Wijers et al. (1998). In addition, until recently it has been thought that the cosmic SFR is a rapidly increasing function of redshift, as estimated primarily from UV luminosities (see Lilly et al. 1996, Madau et al. 1996, Connolly et al. 1997). Both assumptions are very uncertain, and recent work has shown how to improve upon them. First, the measurement of redshifts has shown that GRBs are certainly not standard candles. Schmidt (1999) has calculated the mean peak luminosities and cosmic GRB rates per unit volume using a variety of assumed peak luminosity functions, as well as two choices of redshift evolution and cosmological parameter, q_0, thus eliminating the need for the standard candle assumption. Second, a recent careful analysis of the derivation of the UV luminosity density using deep spectroscopic observations by Cowie, Sangaila & Barger (1999) has considerably reduced the increase of the cosmic SFR with redshift out to $z \sim 1$ compared to earlier estimates. A similar conclusion was reached in the spectroscopic study of compact galaxies with $z<1.4$ by Guzman et al. (1997), using [OII] equivalent widths to estimate the SFR for $z>0.7$ and $z<0.7$.

In the present paper we use these two results to estimate more reliable values of the GRB mean peak luminosity and the rate per unit host galaxy luminosity and find that they are fairly well-constrained. These quantities are then used to re-examine a number of questions. We compare the GRB rates with galactic SN rates in order to constrain the fraction of SN that yield GRBs; even with generous allowance for collimation and a favorable IMF slope, it is difficult to maintain that more than a small fraction of neutron star or black hole-forming events produced GRBs. We then consider the likelihood that GRBs are responsible for most of the HI holes in galaxies and for the melting of chondrules in the early solar nebula. We reach negative conclusions, not so much because of the revised rates and luminosities, but because of empirical constraints not considered in previous work. We do find that GRBs are capable of supplying an intermittent terrestrial surface fluence in excess of that required for direct biological effects (DNA alterations) with a mean time interval of about 8×10^6 yr, suggesting that GRBs may have significantly affected the course of biological evolution during the history of the Earth.

2. GRB Galactic Rates and Mean Peak Luminosities

Earlier estimates of GRB frequencies and mean peak luminosities or energies have assumed that all GRBs have the same luminosity, the "standard candle" assumption (Wijers et al. 1998, Totani 1999, and earlier references given there). Schmidt (1999) has recently estimated the best fit parameters, including the local GRB rate per unit volume and the characteristic peak luminosity, for various assumptions about the GRB peak luminosity function (LF), taken to be a double power law with transition luminosity L_{br} (denoted L* in Schmidt; we reserve L^*_{gal} for the luminosity of the break in the Schecter galaxy luminosity function used below), the redshift evolution of the bursts, and two choices of cosmological parameter q_0 (0.1 and 0.5). Schmidt finds that a very narrow GRB LF, approximating the standard candle model, cannot easily account for the large redshift (3.4) of one of the observed GRBs with known redshift (although Wijers et al 1998 find a median redshift of 3.8 in their standard candle model). There may be a "standard," but somewhat variable, total gamma-ray energy $\sim 10^{52}$ ergs which by collimation and other effects is manifested as a variation in peak luminosity L_{peak} (see, e.g., Kumar & Piran 1999). The current systems with known redshift show that L_{peak} spans two orders of magnitude, even omitting SN 1999bw/GRB 990425, arguing against a standard candle model, as pointed out by Krumholz, Thorsett, and Harrison (1998) when even less variation was known. We compare with the standard candle parameters derived by Wijers et al. (1998) below. Models using luminosity functions instead of standard candles were also presented by Krumholz et al. (1998), who showed that in this case the GRB data could not be used to constrain the cosmic SFR history, since a broad range of models were consistent with available constraints. We adopt this view here, that the SFR history must come from cosmological observations of galaxies.

Schmidt gives derived values for the case with no density evolution (i.e. constant SFR per comoving volume if the GRB rate is proportional to the SFR) and for a strongly increasing density $\propto (1+z)^{3.3}$. We refer to the latter case as the "strong evolution case;" it is similar to the cosmic SFR history to z=1 advocated by Madau et al. (1996) and others. The recent results of Cowie, Songaila & Barger (1999) for the redshift dependence of the SFR from UV luminosity densities, based on a very deep spectroscopic survey that overcomes several problems with earlier UV work, give a much shallower dependence, $\mathrm{SFR}\propto(1+z)^{1.5}$, so we have interpolated between the various models examined by Schmidt in order to allow for this weaker evolution of the SFR, which we refer to as the "intermediate evolution" case. As mentioned above, the Guzman et al. (1997) [OII] study supports this case. The situation remains uncertain, however. The Hα luminosity densities discussed by Yan et al. (1999) suggest that the Hα results might be consistent with the strong evolution case, but this depends on the validity of the local Hα luminosity density derived by Gallego et al. (1995). The Tresse & Maddox (1998) Hα result at z$\sim$0.3 is so much larger than the local Gallego et al. value that it seems possible that the local result is an underestimate. We will quote results for the "intermediate evolution" case, but also give the "no evolution" and "strong evolution" results for comparison, and to show which results and conclusions are sensitive to this uncertainty. We assume that the derived parameters depend only weakly on the assumed SFR history beyond z=1, since the SFR is essentially unknown but may be approximately constant (see Pascarelle et al. 1998, Glazebrook et al. 1998, Tresse & Maddox 1998, Hughes et al. 1998), as assumed by Schmidt (1999).

An important point is that our estimates of probabilities and inter-event times to be derived below only depend on the local source rate per unit area, S, and mean peak luminosity $< L_{\rm peak} >$ as the product $S< L_{\rm peak} >$. (For consideration of galactic HI holes we will require these quantities separately.) Schmidt tabulates a quantity $E_{\rm out}$, which we will refer to as Q. This quantity is equal to the product of the local cosmic GRB rate r_0 (z=0) in units of Gpc^{-3} yr^{-1} (denoted ρ by Schmidt) and the *mean* peak luminosity (in the 50–300 keV range), which is equivalent to our $< L_{\rm peak} >$ for each GRB LF model, i.e. $Q = r_0 < L_{\rm peak} >$. Note that the quantity called L* by Schmidt and tabulated in his Table 1 is *not* the mean luminosity but the luminosity, $L_{\rm br}$, at the break of the assumed double power-law distribution function; we calculated $< L_{\rm peak} >$ as Q/r_0. Thus, aside from scaling the rate per cosmic volume to a rate per unit area of the Milky Way or any other galaxy (see below), the quantity Q is precisely the rate of energy production that enters our calculations. We note the dependence on the Hubble constant H_0 of r_0, $< L_{peak} >$, and Q are $H_0{}^3$, H_0^{-2}, and H_0. In what follows, we adopt $H_0 = 70$ km s^{-1} Mpc^{-1}, as in Schmidt.

Inspection of Schmidt's Table 1 shows that Q is very insensitive to the choice of cosmological parameter q_0 or even the luminosity function model, but depends strongly on the assumed redshift dependence of the GRB rate; for a GRB rate that increases more rapidly with increasing redshift, the GRBs are at larger average distance and must be brighter, but this is outweighed by the much larger volume, reducing the derived local rate. For no evolution, $Q \approx 6 \times 10^{51}$ erg s^{-1} Gpc^{-3} yr^{-1}, while for the $(1+z)^{3.3}$ evolution, Q is between 9.0×10^{50} and 1.5×10^{51} erg s^{-1} Gpc^{-3} yr^{-1} for the various LF models tabulated by Schmidt, and we adopt 1.3 x 10^{51} erg s^{-1} Gpc^{-3} yr^{-1} in that case. Following Schmidt (1999), we have multiplied the tabulated values of Q by a factor of 2.1 to convert from the energy radiated in the 50–300 keV range to that in the 10–1000 keV range. Bearing in mind the Cowie et al. (1999) result, which gives an increase in SFR of 2.8 out to z=1 instead of 9.8 for the strong evolution case, and assuming that the GRBs follow the SFR, we adopt a value of Q for the intermediate evolution case as the average of the no-evolution and strong evolution cases, giving $Q = 3.8 \times 10^{51}$ erg s^{-1} Gpc^{-3} yr^{-1}, with an uncertainty of a factor of two. We realize that there is no best way to interpolate the Cowie et al. evolution between the other two cases, and have chosen to simply adopt the average.

In order to estimate the GRB rate in a given galaxy, say the Milky Way, we avoid the practice of dividing the derived cosmic rate by the total number of galaxies per unit volume derived from the luminosity function, as in Wijers et al. (1998) and elsewhere. This division does give the rate per galaxy of mean luminosity. It does *not* give the rate per L^*_{gal} galaxy as usually quoted; the mean galaxy luminosity can be much smaller than L^*_{gal}, depending on the slope and cutoff of the low-luminosity portion of the adopted luminosity function. The mean number density diverges if this slope is -1 or smaller. Instead, we convert the GRB energy production rate into a rate per unit stellar B-band luminosity by dividing by the B-band luminosity density of galaxies. Recent estimates of the galaxy LF (see Loveday 1997 and references therein) indicate that a Schecter-type function only applies down to a luminosity $L_T \approx 6.6 \times 10^7 L_\odot$, below which the LF is a steep power law with index ~ -2.8 or even steeper. Besides other deep optical LF estimates, this result is also supported by the distribution of galaxy HI masses at very low mass recently reported by Schneider, Spitzak, & Rosenberg (1999). Integrating Loveday's (1997) proposed functional fit of the LF down to $M_B = -12$, we find a blue luminosity density

$$J_{gal,B} \approx 7.6 \times 10^7 h_{70} L_\odot Mpc^{-3}, \tag{1}$$

where $h_{70} = H_0/70$ km s^{-1} Mpc^{-1}. This value is about 30 percent lower than that given by older estimates of the galaxy LF (see, e.g., Peebles 1993), even though the older LFs did not include the low-luminosity increase. Because the low-luminosity power law slope is so steep, this result depends on the adopted low luminosity limit (1×10^7 $L_\odot$ here), and is hence a lower limit.[1]

The luminosity rate per unit volume $Q = r_0 < L_{peak} > = 3.8 \times 10^{51}$ erg s^{-1} Gpc^{-3} yr^{-1} (for the intermediate evolution case) can be converted to a luminosity rate per unit blue stellar luminosity by dividing by $J_{gal,B}$, giving $Q/J_{gal,B} = 5.0 \times 10^{34}$ erg s$^{-1}L_\odot^{-1}$yr^{-1}. This quantity can be converted to a luminosity rate per unit area by multiplication by the mean luminosity surface density in the Milky Way. From Binney & Merrifield (1998), we take a mass surface density in the solar neighborhood $\Sigma = 45$ $M_\odot$ pc^{-2}, and a local value of $M/L_B = 2.3$, giving the blue luminosity surface density $\Sigma_L = 20$ $L_\odot$ pc^{-2}. Then we finally have

$$S < L_{peak} >= Q\Sigma_L/J_{gal,B} = 1.0 \times 10^{36} \text{ erg s}^{-1} \text{ pc}^{-2} \text{ yr}^{-1}, \tag{2}$$

[1] There is still an uncertainty of a factor of two in $J_{gal,B}$ or in the mean number density of galaxies. This is partly because wider angle shallow samples like CfA2, SSRS2, LCRS, Stromlo-APM, and NOG have normalizations that are affected by any relatively local fluctuations (see Marinoni et al. 1999 for a thorough recent discussion of the galaxy LF). It is currently thought that the larger (by a factor of 1.5 to 2.5) normalizations found in deeper, but narrower, surveys like the ESO Slice Project (Zucca et al. 1997) are due to a local underdensity of galaxies (see the discussion and comparisons in Zucca et al. 1997 and Marinoni et al. 1999, and the review by Loveday 1999). Although the results of Loveday (1997) are based on a deep ($b_J < 20.5$) survey, the differences in methodologies, systematic photometric errors, the partial exclusion of low surface brightness galaxies (Sprayberry, et al. 1997) and other effects make this situation confusing. Loveday (1997) points out that because of the method used, his estimate of the normalization is probably an underestimate. Zucca et al. (1997) find a value of $J_{gal,B}$ that is a factor of two larger than given by equation (1) when both are normalized to the same H_0. Given the uncertainties, we continue to use equation (1), but emphasize that our numerical results may need to be revised if the larger value is correct. None of our basic conclusions will be affected.

which is independent of H_0.

Because the relevant quantity for the melting of chondrules or the irradiation of bacteria is the fluence, not flux, we multiply this by an average GRB peak duration, Δt, taken to be 10 sec, the average fluence/peak flux ratio found by Schmidt (1999). This yields $S < L_{GRB} > \Delta t = 1.0 \times 10^{37}$ erg pc^{-2} yr^{-1}. This energy production rate per unit area can be scaled to other galaxies by multiplying by $L_B/L_{B,MW}$, assuming that L_B measures the recent SFR.

Some applications require the mean peak flux or the GRB rate. We tabulate the various quantities in Table 1 for all three evolutionary cases, noting that we take the intermediate evolution result as the most realistic case. The adopted values are for $q_0 = 0.5$. For $q_0 = 0.1$, Q is relatively unaffected, while r_0 is smaller by a factor of about 0.4. Then $< L_{peak} >$ will be larger by a factor of 2.4 and S_{MW} is smaller by a factor of 0.4. It will be seen from equation (7) below, that the probabilities of occurence and average inter-event times for a given received fluence depend only on $< L_{peak} > S \propto Q$ and are insensitive to q_0.

We assume that these results would not be significantly affected if the luminosity dispersion were not due to a range in the intrinsic source luminosities but instead were due to stochastic effects as in the model of Kumar and Piran (1999), as long as the range in the apparent source luminosities is large in both cases.

The standard candle luminosities derived by Wijers et al. (1998) are about a factor of three larger than the mean (*not* L_{br}) luminosities we obtain from Schmidt for the strong evolution case, but a factor of two smaller than ours in the no evolution case. The use of a LF has reduced the dependence of mean peak luminosity on evolution model, as can also be seen from Schmidt's examples. On the other hand, the standard candle cosmic rates (Gpc^{-3} yr^{-1}) are a factor of three smaller in both cases, an effect which is not seen in Schmidt's standard candle cases. The Schmidt results refer to the 10–1000 keV range, while Wijers et al. use the 30–2000 keV range, but this should not contribute much to the difference in results. Part of the difference arises from the different statistical constraints used, since Wijers et al. were matching the number-flux distribution, while Schmidt matched $<V/V_{max}>$ and the total number of events; yet Schmidt's models do match the observed flux distribution (his Figure 2c). It would be interesting to compare results based on the same statistical constraints.

We next use these derived quantities to examine some astrophysical and biological implications.

3. GRBs and Supernovae

In the context of models in which GRBs arise in massive stars, it is interesting to consider the rate of occurence of GRBs in comparison to SN. Supernova rates are typically given in units of number per 10^{10} $L_\odot$ of luminosity in the blue band per century, known as a "supernova unit" or SNu. The rates for GRBs can be cast easily in these units by dividing the derived local rate per unit volume, r_0, from Table 1 by the local density of galactic blue light, $J_{\rm gal,B}$ as described in §2. The result is 8.7, 4.7 and 0.7 $\times$ 10^{-5} ${h_{70}}^2$ SNu.

Cappellaro et al. (1997) give rates for Type Ib/c and Type II supernovae (SN Ib/c; SN II) as a function of galaxy type. The rate of SN Ib/c averaged over galaxy types Sbc-Sd is 0.14 $\pm$ 0.07 ${h_{70}}^2$ SNu. The rate for SN II is about a factor of 5 higher with similar uncertainty. The ratios of the rate of SN Ib/c supernovae in Sbc-Sd galaxies compared to the rate of GRBs are 1,600, 3,000, and 20,000 for no, intermediate, and strong star formation evolution, respectively. The ratios would be higher by about a factor of 3 if one considered SN rates in Sc galaxies alone. There have been suggestions of correlations of GRBs with some SN II (Germany et al. 1999), although physical constraints associated with the thick hydrogen envelope suggest that it would be difficult to generate the requisite relativistic flows in that environment (MacFadyen & Woosley 1999). If GRBs were to be associated with SN II the ratios of rates would be higher by a factor of about 5. These ratios could all be reduced by a factor of $\Delta\Omega/4\pi$ if all GRBs are collimated by the same universal amount. Factors of $\Delta\Omega/4\pi = 0.003$ to 0.01 are discussed in the literature for some events (see Wheeler 1999 for a review). There could also be variations in apparent brightness, deduced peak luminosity, and hence rates, due to fluctuations in the γ-ray emissivity within a collimated beam (Kumar & Piran 1999). It is certainly not clear, however, that all GRBs are subject to the same collimation. It may be that only a fraction, perhaps only those bursts with extremely high isotropic equivalent energy, are substantially collimated. If most bursts are subject to relatively small collimation, then the GRB rates derived by Schmidt (1999) ignoring collimation would still represent a good approximation to the mean rates adjusted for collimation.

The ratios of SN to GRB rates are relevant to a variety of astrophysical issues and to the nature of the GRBs themselves. In particular, they represent constraints on the currently popular picture that GRBs are associated with star formation (the ansatz behind Schmidt's calculation) and hence that they arise in the collapse of massive stars to produce black holes (MacFadyen & Woosley 1999) or rapidly spinning neutron stars (Wheeler et al. 1999). If collimation is not a significant factor in the mean rates derived by Schmidt, but only, for instance, in the rare bursts with exceptionally high isotropic equivalent energy, then GRBs must be extremely rare. If, for instance, they only come from stars more massive than a given threshold value, then that threshold must be exceedingly high.

As an illustration, if the integrated number of stars with mass above some value, M, scales as M^{-n}, GRBs occur for all stars above a threshold, $M_{GRB>}$, and SN occur in stars with mass in excess of $M_{SN>}$, then $M_{GRB>} = M_{SN>}\ (N_{SN}/N_{GRB})^{1/n}$. Note that the actual value of the supernova threshold is not too important since it just enters linearly; we take 10 $M_{\odot}$ as a representative value. The value of n is 1.3 for a Salpeter mass function and n = 1.8 represents a steeper, but still reasonable, mass function (see Scalo 1998 for a critical review of cluster IMFs). For the ratios given above and a Salpeter slope, GRBs could only occur for stars with a mass in excess of $M_{GRB>} = 2900$, 4700, and 20,000 $M_{\odot}$, for no, intermediate, and strong SFR evolution, respectively. For a steep slope, n = 1.8, the numbers would be $M_{GRB>} = 600$, 860, and 2500 $M_{\odot}$, respectively. If SN II rates were adopted, these mass limits would all be increased by a factor of 2–4, depending on the slope of the mass function. Clearly, if collimation or some other effect does not significantly alter the rates given by Schmidt, GRBs cannot arise by "normal" black hole formation, nor can they be driven by the birth of every magnetar, which represent a fraction of order 10 percent of "normal" pulsars.

In the extreme case that *all* GRBs are associated with significant collimation, it is still difficult to avoid the conclusion that they are a rare stellar event. For the assumption that all GRBs are collimated by a factor of $\Delta\Omega/4\pi = 0.01$, the ratios of SN Ib/c to GRBs would give threshold values of $M_{GRB>} = 84$, 140, and 590 for n = 1.3 and 47, 66, and 190 for n = 1.8, respectively.

This analysis suggests that GRBs can only come from a very small fraction of stars, either very massive stars or a very small mass interval or a small fraction of stars that otherwise undergo similar behavior, for instance forming black holes or magnetars. The situation for an origin in SN Ib/c progenitors is somewhat more conducive than for SN II. We note the caveat that, while SN Ib/c are thought to be associated with massive stars, their progenitor evolution is unknown, so assigning a minimum mass to GRBs on the basis of rates may not be entirely appropriate. In particular, if SN Ib/c require binary evolution and mass transfer then they do not sample the initial mass function in any straightforward way. Given the empirical rates, however, it is clear that even with substantial collimation of GRBs, there are large ranges of reasonable parameter space where GRBs must represent extremely massive progenitors or otherwise select a tiny portion of the total mass range available to SN Ib/c progenitors. Only if one goes to a carefully selected (but not impossible) portion of parameter space, for the smallest observed SN rates per blue luminosity, for steep mass functions, and for little cosmic evolution of the GRB rate (thereby vitiating the assumption that GRBs are associated with massive stars), does one find minimum progenitor masses as low as 30 $M_\odot$, a plausible minimum mass to produce black holes (Twarog & Wheeler 1982, Fryer, 1999).

The results for the combination of parameters that seem most reasonable to us, namely intermediate redshift evolution, little collimation for the average burst, an average SN rate for Sbc-Sd galaxies, only SN Ib/c (not SN II) being associated with GRBs, and in addition using a steep IMF index of n = 1.8 (steeper than most claims in the literature) gives $M_{GRB>}$ approximately 100 $M_\odot$ or larger. Only if strong collimation is the rule for the average GRB can this threshold be lowered to the mass range where black hole formation is routinely expected to occur. The situation becomes even more extreme if one or more of the following obtain: strong cosmic evolution, comparison is made to SN II supernova rates, or an IMF as flat as n = 1.3. It thus seems that routine black hole formation cannot play a role in producing GRBs. It may be that only special cases with exceptionally high initial stellar rotation or magnetic field can generate a GRB. The same statement applies to models based on rapidly rotating, highly magnetized neutron stars. Only a tiny fraction of such events, perhaps again those with exceptionally strong rotation and magnetic field even within the category of magnetars could contribute GRBs.

Finally, we note that, despite their large energy, the low rate of GRBs compared to supernovae means that GRBs are unlikely to have a significant impact on induced star formation or on nucleosynthesis except, perhaps, for some rare species that might be specifically produced in GRBs.

4. GRBs and HI holes in galaxies

It has been long known that very large, shell-like structures exist in the HI distribution of the Milky Way (Heiles 1979) and other galaxies (Brinks 1981), from large disk galaxies like M101 to dwarf galaxies like the SMC and IC 2574 (see Wilcots & Miller 1998, Staveley-Smith et al. 1997, Kim et al. 1998, Walter & Brinks 1999, and references therein; see Walter 1999 for a review). A typical galaxy has 50–500 shells/holes with sizes in the range 0.1–1 kpc and typical ages of 10^7 yr. The possible processes for producing such structures have been extensively discussed (e.g. Tenorio-Tagle & Bodenheimer 1988, Walter 1999), with a leading candidate being winds driven from young clusters by OB star winds and multiple supernovae. Such a model successfully accounts for the size distribution of hole sizes in the SMC (Oey & Clarke 1997), although there are problems for other galaxies, and possibly for the assumed importance of stalled shells in that work (Walter & Brinks 1999). There may also be a problem with the energy required to account for the largest holes, although this might require a different process for only a small percentage of the holes. Recently Rhode, Salzer, & Westpfhal (1999) failed to detect the expected residual populations of the putative OB associations responsible for the holes in the dwarf galaxy Ho II, leading them to suggest some other mechanism is required (see however the cautionary remarks in Efremov, Elmegreen, & Hodge 1998 and Walter & Brinks 1999). Efremov et al. (1998) and Loeb & Perna (1998) have independently suggested that GRBs could be the primary process responsible for the HI holes (see also Efremov 1999a,b for arguments specifically aimed at stellar arcs and a supershell in the LMC). It is therefore of interest to examine the viability of GRBs as an explanation for most of the HI holes in light of the values for GRB peak luminosities and galactic rates we have inferred from Schmidt (1999) and the reduction in SFR redshift evolution based on Cowie et al. (1999).

In order to test the GRB hypothesis for HI holes, we assume that the explosions are spherically symmetric, since this is the most optimistic case. Our best choice value of $< L_{peak} >$ is 1.1×10^{51} erg s^{-1}. Using the fluence/flux ratio of 10 sec estimated by Schmidt, and assuming an efficiency for conversion of kinetic energy to radiation of $\epsilon = 0.01$, as assumed by Efremov et al. (1998) and Loeb & Perna (1998) and supported by arguments given by Kumar (1999), we obtain an average kinetic energy of $E = 1.1 \times 10^{54}(\epsilon/0.01)^{-1}$ erg. Using the same late phase blast wave scaling relation as used by Efremov et al. and Loeb & Perna (Chevalier 1974) shows that a typical shell should slow down to 10 kms^{-1} at a radius $R_{kpc} = 0.7\ {E_{54}}^{0.32} n^{-0.36}$, where n is the ambient gas number density, assumed uniform. We take n=1 cm^{-3}, although there is some evidence that the average particle density may be somewhat smaller in the "puffed up" dwarf IC 2574 and other dwarf galaxies (see Walter & Brinks 1999). The time at which this radius is reached is $t = 20\ {E_{54}}^{0.32} n^{-0.36}$ Myr. Since the energy found here is very similar to that assumed by Efremov et al. (1998) and Loeb & Perna (1998), we agree with their conclusion that GRBs can account for the sizes of shells and their estimated ages using the adopted parameters. We realize that the value of ϵ is controversial; if ϵ is as large as 0.85, as claimed by Fenimore & Ramirez-Ruiz (1999), and/or significant collimation occurs in the majority of cases, the effectiveness of GRBs for explaining galactic HI holes will be compromised with respect to accounting for the observed sizes and ages.

The GRB hypothesis fails, however, to account for the observed large number of holes observed in many dwarf galaxies, even if ϵ is as small as assumed. Following Loeb & Perna (1998), the average number of holes observed at any time should be approximately equal to the ratio of the mean shell age (as given above) to the mean time between GRB, which is the inverse of the GRB rate. The masses of many of the galaxies in which numerous holes are found are much smaller than the Milky Way, so the rates are much smaller than estimated for the Milky Way, leading to large times between events and therefore an unacceptably small prediction for the number of shells. For example, consider the M81 Group dwarf IC 2574 studied by Walter & Brinks (1999), the luminosity of which is $L_B = 8 \times 10^8$ $L_\odot$. Using our best estimate for the GRB rate per unit luminosity, $4.7 \times 10^{-17} yr^{-1}$ L_B^{-1}, with L_B in solar units, the mean GRB rate should be 3.8×10^{-8} yr^{-1}, corresponding to a mean time between events of 30 Myr. Thus the probability of observing even one shell of size and age given above is less than unity for this galaxy, while at least 50 holes are observed by Walter & Brinks. Uncertainties in the GRB rate estimates of a factor of two orders of magnitude would be needed to reconcile the predictions with the observations. Similarly, no reasonable decrease in the assumed density could yield agreement. A similar disparity occurs for other dwarf galaxies, including Ho II (Puche et al. 1992, Rhode et al. 1999) and the SMC (Staveley-Smith et al. 1997), where large numbers of large holes are observed even though these galaxies are somewhat fainter than IC 2574. Even in the Local Group dIrr galaxy IC 10, where only 7–8 HI shells were found by Wilcots & Miller (1998), the discrepancy remains large, since the luminosity of IC 10 is only $L_B \approx 2.4 \times 10^8$ $L_\odot$. The expected GRB rate is more than three times smaller than given above for IC 2574, and the probability of even a single hole is smaller by the same factor. The radii of all of the shells in IC 10 are only around 50pc, requiring small explosion energies and reducing the discrepancy somewhat in this case.

Note that if the case of maximum evolution $(1 + z)^{3.3}$ were adopted, the situation becomes much worse, because the average cosmic rate, and hence specific rate per unit mass or luminosity, decreases by a factor of seven. The difference between our conclusion and that of Loeb & Perna (1998) is therefore primarily due to these authors neglecting to notice the small masses of many of the galaxies with numerous holes. Models based on winds driven by multiple SN do not suffer from this disparity because, even though 100–1000 SNe may be required to explain the large holes, the rate of SNe is apparently many orders of magnitude larger than the rate for GRBs if the latter are assumed to emit isotropically. Similarly, we find that the statement by Efremov et al. (1998) and Efremov (1999a,b) that 4–5 very large HI shells or arcs in the LMC could have been produced by GRBs over the past 10^7 yr is untenable, especially considering the relatively small mass of the LMC and its present SFR.

It is still possible that a small number (of order unity) of holes per galaxy could be due to GRBs, even if the explosions are initially highly collimated. At the large sizes and ages at which the GRB explosions would be observed as large HI holes, the collimation could have decreased considerably. It may still be possible to use GRBs to explain arc-like structures that require very large energies.

The ability of spherically-symmetric GRB explosions to account for the largest HI holes ($\sim$ 1.4kpc in radius) is, however, somewhat compromised because the production of such a hole requires a GRB energy of about 8 $\times 10^{54}$ erg, while the distribution of GRB energies is likely a decreasing function of energy. For example, using a peak luminosity function N(L) $\sim$ $L^{-1.5}$, a slope between the two high-luminosity power law slopes adopted by Schmidt (1999), energies this large are expected in only a fraction $\sim$ 5×10^{-5} of events. GRBs might still account for the most luminous SNRs, for example the hypernova candidates in M101, if the energy is not severely collimated. Contrasting views are given by Wang (1999) and Chu, Chen & Lai (1999). Hydrodynamic simulations can probably help resolve the question of the association of GRBs with the M101 hypernova remnants (Kim, Mac Low & Chu 1999). Whatever the resolution of this question, we only claim to have shown that the GRB rate is far too small to account for most of the large HI holes in galaxies.

5. A Poisson Model for Fluence Probabilities

For some of the applications of interest it is necessary to estimate the probability that a GRB occurred within a distance $\ell_{\rm cr}$, such that the fluence received at a given point exceeds a critical value $F_{\rm cr} = E_{\rm s} / 4\pi{\ell_{\rm cr}}^2$, where $E_{\rm s}$ is the total energy emitted by the burst. Although the GRB events in a given galaxy are likely to be clustered, in order to make such an estimate we assume that the GRB events are randomly distributed in space and time and can be described by a Poisson spatial process. If we observe the process over time, and mark the distance of the nearest event, this nearest distance decreases with time, as the number of "markers" increases within a given volume or area. We are therefore interested in the probability distribution for the distance of the nearest event as a function of time. It will be seen that the accumulated nearest event distances are large compared to a galactic scale height, because of the relatively small rate of GRBs. Thus we consider a two-dimensional Poisson process. (By contrast, supernova events are frequent enough that the appropriate distribution of markers would be three-dimensional.) We also make our estimates using the mean GRB energies and total rates, rather than including the effect of the GRB luminosity function on the calculation, since we are interested in order of magnitude results at this point.

Let S be the rate of GRB events per unit area and A the area of interest. The number of accumulated events per unit area after time t is ν = St. Then the probability that k events have occurred in an area A during time t is

$$P(k) = (\nu A)^k \exp(-\nu A)/k! \tag{3}$$

Let ℓ be the distance to the nearest marker. The probability that a circle of area A contains zero markers is P(0)=exp($-\nu$A). This is equivalent to the probability that the first (i.e. nearest) marker occurs at a distance greater than that corresponding to area A. The value of P(0) is thus the cumulative probability distribution of nearest distances corresponding to area A, $\Phi(> A)$. By definition,

$$\Phi(> A) = \int_A^\infty \phi(A) dA, \tag{4}$$

where $\phi(A)$ is the differential distribution or probability distribution function (pdf) of nearest distances corresponding to A. The function $\phi(A)$ is obtained by differentiating $\Phi(> A)$ as $\phi(A) = \nu\exp(-\nu A)$. Transforming this pdf to the pdf of the nearest distance, $p(\ell) = \phi(A(\ell))$, where $A = \pi\ell^2$, gives

$$p(\ell) = 2\pi\nu\ell \exp(-\pi\nu\ell^2). \tag{5}$$

In statistics texts this is usually given as the distribution of nearest neighbors, but it is clear that it is equivalently the probability distribution of nearest distances from any point. By integration, the mean nearest distance is

$$\bar{\ell} = (St)^{-1/2}/2. \tag{6}$$

For the intermediate redshift evolution parameters, we find that $\bar{\ell} = 510\ t_{Gyr}^{-1/2}$ pc, where t_{Gyr} is time in units of 10^9 yr. For the no evolution and strong evolution cases, the numerical coefficient is 370 pc and 1390 pc, respectively.

The probability that a GRB has occurred at a distance less than ℓ_{cr} (corresponding to the critical received fluence F_{cr}) in time t is obtained by integrating $p(\ell)$ from 0 to ℓ_{cr}. The result is

$$P(\ell < \ell_{cr}) = 1 - \exp[-(\pi/4)(\ell_{cr}/\bar{\ell})^2]. \tag{7}$$

The argument of the exponential is

$$(\pi/4)(\ell_{\rm cr}/\bar{\ell})^2 = \frac{< \rm L_{peak} > \Delta t\ St}{4F_{cr}} \qquad (8)$$

where the mean energy release per event has been written as the mean peak luminosity $< L_{peak} >$ times some average duration Δt ($\approx$10 sec, see above), and

$$\ell_{\rm cr} = (< \rm L_{peak} > \Delta t/4\pi F_{cr})^{1/2}, \qquad (9)$$

is the critical distance for an event that results in a a fluence $\rm F_{cr}$. Equating the argument of the exponential in equation (7) to unity gives the average time between events that produce a received fluence $\rm F_{cr}$ as

$$\rm T = 4F_{cr}/ < L_{peak} > \Delta tS. \qquad (10)$$

To indicate the dependence on the cosmic SFR history, we take for illustration a fiducial critical fluence of 10^9 erg cm^{-2}, giving $\ell_{\rm cr} = 290\ \rm F_{cr,9}^{-1/2}$ pc. This result is changed by less than fifty percent if we consider the no evolution and strong evolution cases. The mean time between significant ($\rm F>F_{cr}$) events in the Galaxy is, from equation (10), $\rm T = 3.8 \times 10^9\ F_{cr,9}$ yr for the intermediate evolution case. For no evolution and strong evolution, the numerical coefficient becomes 2.3×10^9 and 1.2×10^{10}, respectively. The strong (no) evolution case gives larger (smaller) interevent times because the local GRB rate is smaller (larger) in that case.

The above derivation approximates the full LF of the peak luminosities of GRBs by the *mean* peak luminosity. More realistically, the above probabilities would represent conditional probabilities for a specified luminosity, which would then have to be integrated over the LF to find the probability for a given critical fluence. For example, Schmidt's (1999) adopted LFs would give a larger number of events below the mean peak luminosity, somewhat reducing the estimated probabilities and increasing the derived average time. On the other hand, for Kumar & Piran's (1999) stochastic model, the effective LF is much more symmetrical about the mean, with a significant fraction of events at larger and smaller luminosities than the mean, suggesting that our estimates based on the mean luminosity would be essentially unchanged.

6. GRBs and Chondrules

Chondrules are submillimeter-sized meteoritic silicate inclusions that appear to have solidified by cooling after rapid heating during the first 10^7 yr of the history of the solar system. The nature of the heating process that melted the chondrules in the early solar system has remained enigmatic for many years. A detailed review of the empirical constraints and most of the proposed heating models has been given by Jones et al. (2000). Recently McBreen & Hanlon (1999) have made the intriguing suggestion that GRBs could supply the fluence required to melt the chondrules. One piece of evidence in favor of this idea is that the textures and other properties of chondrules imply that the heating event was short lived, probably less than a minute, in agreement with the few second average GRB duration. Since McBreen & Hanlon assumed a very large GRB energy, and because we are unable to reproduce the rates that were adopted, it is of interest to re-examine the question.

McBreen & Hanlon (1999) estimate that 2×10^{10} erg g^{-1} is needed for melting of chondrule precursors and calculate the minimum GRB fluence required to produce chondrule layers of thickness 0.18, 0.8, and 2 g cm^{-2} as 1.8×10^{10}, 7.0×10^{10}, and 1.5×10^{11} erg cm^{-2}. We adopt these values in the present calculations.

We need to estimate the probability $p(F_{cr})$ that such a fluence occurred during the first 10^7 yr of the life of the solar nebula. For a two-dimensional Poisson process the result given above (equation 7) yields

$$p(F_{cr}) = 1 - \exp[-(\pi/4)(\ell_{cr}/\bar{\ell})^2], \tag{11}$$

where ℓ_{cr} is the critical distance at which a GRB of fluence $< L_{peak} > \Delta t$ can produce a fluence F_{cr} at the sun and $\bar{\ell}$ is the mean distance expected for GRB markers after time 10^7 yr, given the rate per unit area of the events. Using our best estimates for the mean GRB fluences, we find that the three values of F_{cr} given above correspond to ℓ_{cr} = 680, 350, and 240 pc, for no, intermediate, and strong evolution, respectively. For the GRB rate per unit area in the solar vicinity at the time of solar system formation, we follow McBreen & Hanlon (1999) and allow for the possibility that the sun was formed in a spiral arm, where the SFR may be larger. Whether spiral arm passage actually enhances the SFR per unit gas mass, or instead simply increases the gas density and hence only the SFR per unit volume, is still a contentious issue. A detailed discussion of various considerations is given in Elmegreen (1997). Based on these considerations, we increase the average GRB rate that we derived for the Milky Way, per unit area, by a factor of three to account for the spiral arm effect. This gives $\bar{\ell} = 3000$ pc $(t/10^7 \text{ yr})^{-1/2}$. For the three critical fluences, the probability $p(F_{cr})$ is 2.2×10^{-2}, 5.6×10^{-3}, and 2.6×10^{-3}. These probabilities are actually larger than given by McBreen & Hanlon; however, rather than *assume* that GRBs formed the chondrules and then conclude that chondrules are very improbable for *other* planetary systems, it seems more reasonable to us to conclude that GRBs are an improbable source of heat for solar system chondrules.

The situation is actually more pessimistic than this. McBreen & Hanlon fail to consider the strong evidence that a significant fraction, if not most, chondrules, have experienced more than one heating event (Rubin & Krot 1996), although they point out the possibility without further discussion. For example, many formations consist of chondrules within larger chondrules. We can estimate the probability that the primitive solar nebula was subjected to two heating events during its first 10^7 yr from the Poisson spatial model (equation 3), for which the probability of two events within area A during time t is

$$p(2) = (1/2)(\mathrm{StA})^2 \exp(-\mathrm{StA}), \tag{12}$$

where S is the rate per unit area. This expression is only valid as long as $\ell_{cr}/\bar{\ell}$ is not so large that three or more events have occurred, a condition easily satisfied in the present case. Using $A = \pi {\ell_{cr}}^2$ and $St = 1/4\bar{\ell}^2$, we get

$$p(2) = (1/2)[(\pi/4)(\ell_{cr}/\bar{\ell})^2]^2 \exp(-(\pi/4)(\ell_{cr}/\bar{\ell})^2]. \tag{13}$$

Using our best estimate for the rate and mean fluence and the three sample critical fluences adopted by McBreen & Hanlon, we find $p(2) = 2.4 \times 10^{-4}$, 1.6×10^{-5}, and 3.4×10^{-6}, respectively. Thus it is clearly unlikely that GRBs contributed to the multiple heating of the chrondrules.

7. GRBs and Biological Evolution

It was shown above that the probability that the solar system has received a fluence of 10^{10} – 10^{11} erg cm^{-2} from GRBs during its first 10^7 yr is very small. We next examine a similar question, with more interesting ramifications. What is the probability that the Earth's surface has been irradiated by a gamma-ray fluence capable of causing significant DNA alterations during the Earth's history, and, if this probability is greater than unity, what is the mean time between significant terrestrial events? We emphasize that we are interested in stochastic effects that could affect biological evolution at any level, and are not specifically concerned with catastrophes like mass extinctions induced either directly or through changes in atmospheric chemistry; see Ruderman (1974), Crutzen & Bruhl (1996), Collar (1996), Ellis, Fields, & Schramm (1996), Thorsett (1995), Dar et al. (1996) for discussions focusing mainly on supernova explosions; only the latter two papers discussed GRBs, but they were concerned with ozone layer destruction, production of local radioactive species, and showers of atmospheric muons that can penetrate underground and underwater, topics which we do not address here.

In order to understand the possible biological importance of GRBs, the critical γ-ray (and X-ray — see below) fluences that are typically required for significant DNA alterations must be estimated. It is generally agreed that damage at all large-scale levels (e.g. organisms, organs) traces to cell damage, and that damage to DNA, in the form of single and double strand breaks, base damage, combinations of complex breaks, and cross-linking within DNA or with protein, is apparently implicated in most cellular effects, including mutation, chromosome aberrations, and cell killing and transformation (see papers in Fielden and O'Neill 1991; for a modern textbook account see Alpen 1998). For the lower part of the energy range of interest here (10–1000 keV), the main effect is ionization, which weakens or breaks valence bonds; also, any unpaired electrons left in covalent bonding will be very reactive and can cause cross-bonding of molecules, synthesis of new molecules, or polymerization. At higher energies, Compton scattering becomes important, and then, above about 1 MeV, pair production can occur. Additional aspects of the problem include, for example, the effect of oxygen in increasing the photosensitivity of biological material (the "oxygen effect"). These "dose-modifying" processes should not affect our order-of-magnitude estimates (for a review of radiosensitization see van der Schans 1991).

Biological damage is almost always quantified in terms of the dose of radiation absorbed, usually in units of rads (1 rad = 100 erg g^{-1} absorbed; more recent literature uses the Gray, 1 Gray=100 rad). The photon fluence (in erg cm^{-2}) required to produce 1 rad of damage depends on energy stopping power or linear energy deposition ("LED," erg cm^{-1} here) and the density of the material of interest, and so depends on energy. A dose of 1 rad is equivalent to about 5000 erg cm^{-2} for photon energies between 0.1 and 100 MeV in water, but the conversion factor decreases rapidly for smaller photon energies and at 20 keV the conversion factor is only 200 erg cm^{-2} (see Figure 10-3 of Andrews 1974). We realize that the biological effects cannot be quantitively parameterized simply in terms of the absorbed dose (spatial distribution of damage, temporal phase of cell activity, and other factors are also significant), but the "quality factor" and "relative biological efficiency" that are introduced to account for these variations are usually of order one to a few, although larger variations do occur. It should also be noted that total absorbed dose (or fluence) is not the only important factor in biological radiation damage: the dose rate (which can be converted to a flux, as above for absorbed doses and fluences) may be of crucial significance. For example, damage fluxes may be bounded on the low side partly because of the existence of cell repair mechanisms that only have time to operate when the flux is small enough.

The energy νF_ν at which the flux peaks in most GRBs is about 200 keV with a tail in the distribution of peak energy extending to ∼1MeV (Band et al. 1993), although it will be seen below that the energy probably reaches the Earth's surface in the form of X-rays. An interesting and useful result for our perspective is that a large variety of cellular and whole organism damage occurs for a fairly narrow range of absorbed γ-ray and X-ray doses. A number of studies of DNA single- and double-break damage, chromosomal aberrations, cross-linking, and other types of damage induced by exposure of mammalian cells and human lymphocyte cells by 5–100 keV X-rays and MeV gamma-rays all suggest an effective dose of $100 - 1000$ rads for significant damage (see papers by Iliakis et al., Radford, Frankenberg, Sasaki, & Edwards in Fielden and O'Neill 1991; also Bird et al. 1980, Geard 1982, Wilson et al. 1993), which corresponds to a fluence of 5×10^5 to 5×10^6 erg cm^{-2} for gamma rays. The level of "damage" required for significance in biological evolution is highly uncertain, and may be much smaller. For this reason we think that a conservative estimate of the critical fluence is the lower limit of gamma ray damage fluences quoted above, $F_{cr} = 5 \times 10^5$ erg cm^{-2}. For X-rays, taking into account the larger cross section, we adopt $F_{cr} = 2 \times 10^4$ erg cm^{-2}, corresponding to a photon energy of 20 keV.

Because of atmospheric attenuation, the critical fluence required above the Earth's atmosphere must be increased above the critical surface value given above. For γ-rays the attenuation problem depends primarily on the total column density of the atmosphere, although the elemental composition is important because the radiative transfer is essentially controlled by a series of interactions involving atomic absorption edges. The layer of optical depth unity in the atmosphere lies about 30 miles above the surface; however, unlike softer radiation, e.g. X-rays or UV, the interaction of γ-rays in the atmosphere is not by means of absorption, but by scattering. At each interaction, the γ-rays are not stopped, but degraded to lower energy photons. As this happens the cross section rises, but Monte Carlo simulations, including forward scattering effects (to be published elsewhere), show that of order 40 scatterings are required to degrade the incident photons to 10 keV X-rays where they will be absorbed by iron K-shell electrons. So while the single scattering optical depth of the atmosphere is about 30, the net optical depth to totally destroy the incoming γ-rays is only about $30/(40)^{1/2}$, or about 5. Thus one expects that of order e^{-5} ∼1% of the incident gamma ray energy may actually reach the ground, but in the form of X-rays. The simulations give about the same result. This means that the effective critical fluence should be increased by a factor of 100, to take into account the attenuation of energy. The appropriate above-the-atmosphere fluence corresponding to a critical dose is that for 20 keV X-rays given above. This yields $F_{cr} = 2 \times 10^6$ erg cm^{-2}.

In this case $\ell_{cr} = 6500$ pc, so even a very distant GRB with the adopted mean source fluence will be capable of biological affect. Recalling that the average nearest event distance is $\bar{\ell} = 510\ t_{Gyr}^{-1/2}$ pc for the intermediate evolution case (370 and 1390 pc for the no evolution and strong evolution cases), it is clear that biologically significant photon "jolts" from GRBs must have been frequent during the Earth's history. Using equation (10) we find that the mean time between significant events is $T = 7.8 \times 10^6$ yr for the intermediate evolution case. For no evolution and strong evolution, T is changed to 4.5×10^6 yr and 2.4×10^7 yr, respectively. Thus for the intermediate evolution case *about 500 biologically significant Galactic photon irradiations should have occurred stochastically during the 4.6 Gyr history of the Earth.*

It is interesting to note that only one hemisphere of the Earth would have been irradiated at the time of each event, since the event duration is of order 10 sec (neglecting the extended, but less powerful afterglow). Interesting consequences also follow by considering the protection afforded by various coverings. For example, the opacity of water at 20 keV is about 0.5 cm^2 g^{-1}, so organisms below about 1 cm of water would have been protected. For surface materials (e.g. rocks, leaves) the cross sections and densities are larger, so the shielding depth is much smaller. An interesting but very speculative possibility is that the long-term viability of surface-dwelling organisms might have only been possible because of an unusually long lull between the stochastic photon irradiations. At present there is little known about why the transition of life from ocean to land occurred, although a common speculation is that the transition required the development of a significant ozone layer due to oxygen injection by bacterial photosynthesis and geological erosion. Currently the timing of the two events is too uncertain to test this idea. The present work offers an alternative explanation — a lucky lull in Galactic activity.

¿From an opposite point of view, it is not clear that non-catastrophic hypermutation due to photon jolts at intervals of 10^7 or so years would have significant effect on the phenotype of species; instead the result might be "silent mutations." Examples include plant mitochondria with extreme rates of mutational change, the plant and animal populations around Chernobyl, and the rain forests seared by radiation release experiments in Puerto Rico (A. Ellington, private communication).

We note that the biologically-significant fluence adopted above does not apply to all organisms. For example, the bacterium Deinococcus radiodurans (formerly Micrococcus) and other members of its genus are remarkably resistant to extremely large doses of ionizing and UV radiation, because of exceedingly efficient DNA repair (see Minton 1994, Battista 1997 for reviews). The critical fluences for γ ray damage are about a factor of 10^2 larger than adopted here for "normal" bacteria, but we are aware of no experiments involving X-rays. If the increase in critical fluence is the same for X-rays, then it is unlikely that D. radiodurans has been exposed to a near-lethal dose from GRBs during the history of the Earth. The possible importance of ultraviolet radiation from supernovae during their light curve evolution with respect to D. radiodurans will be discussed elsewhere.

Finally, we point out that although we have found GRBs to be of potential biological importance as sources of stochastic irradiation events, it is by no means clear that they are the most important. Other events, such as the ultraviolet burst associated with SN shock breakout, the ultraviolet radiation and radioactive decay γ-rays from SN light curves, soft γ-ray repeaters, flare stars, or massive spectral type O stars may make important or even dominant contributions to this Galactic background of stochastic irradiation events. We postpone a discussion of these other sources to a separate publication.

Acknowledgements

We thank Peter Höflich for performing gamma-ray atmospheric attenuation calculations, Andy Ellington for pointing out the possibility of "silent mutations," and Charles Cockell for stimulating discussions on the biological aspects of this work. This research was supported by NSF grants AST 981960, 9907582, and 9903582.

REFERENCES

Alpen, E.L. 1998, Radiation Biophysics, 2nd ed. (New York: Academic Press)

Andrews, H. L. 1974, Radiation Biophysics (Edgewood Cliffs: Prentice-Hall)

Band, D. et al. 1993, ApJ, 413, 281

Battista, J.R. 1997, Ann. Rev. Microbiology, 51, 203

Binney, J. & Merrifield, M. 1998, Galactic Astronomy (Princeton: Princeton University Press)

Bird, R. P., Rohrig, N., Colvett, R. D., Geard, C. R., & Marino, S. A. 1980, Radiation Research, 82, 277

Bloom, J. S. et al. 1999, Nature, submitted, (astro-ph/9905301)

Brinks, E. 1981, A&A, 95, L1

Cappellaro, E,, Turatto, M., Tsvetkov, D. Yu., Bartunov, O. S., Pollas, C., Evans, R., & Hamuy, M. 1997, A&A, 322, 431

Chevalier, R. A. 1974, ApJ, 188, 501

Chu, Y-H., Chen, C.-H. R., & Lai, S.-P. 1999, preprint, (astro-ph/9909091).

Collar, J. I. 1996, Phys. Rev. Lett., 67, 999

Connolly, A.J., Szalay, A.J., Dickinson, M., SubbaRao, M.U., & Brunner, M.J. 1997, ApJ, 486, L11

Cowie, L.L., Songaila, A., & Barger, A.J. 1999, ApJ, 118, 603

Crutzen, P.J. & Bruhl, C. 1996, Proc. Natl. Acad. Sci, 93, 1582

Dar, A., Laor, A. & Shaviv, N.J. 1996, preprint, (astro-ph/9607160)

Efremov, Yu. N. 1999, ARep, 43, 284

Efremov, Yu. N. 1999, AstL, 25, 74

Efremov, Y. M., Elmegreen, B. G. & Hodges, P. W. 1998, ApJ, 501, L163

Ellis, J., Fields, B. D. & Schramm, D. N. 1996, ApJ, 470, 1227

Elmegreen, B.G. 1997, in The Formation of the Milky Way, ed. E.J. Alfaro & A.J. Delgado

(Cambridge: Cambridge Univ. Press), p. 28

Fenimore, E.E. & Ramirez-Ruiz, F. 1999, ApJ, submitted, (astro-ph/9909299)

Fielden, E. M. & O'Neill, P. 1991, The Early Effects of Radiation on DNA (NY: Springer-Verlag)

Fryer, C. L. 1999, 1999, ApJ, 522, 413

Galama, T. et al. 1998, Nature, 395, 670

Galama, T. et al. 1999, ApJ, in press, (astro-ph/9909299)

Gallego, J. Zamorano, J., Aragon-Salamanca, A., & Rego, M. 1995, ApJ, 455, L1

Geard, C.R. 1982, in Radiation Biology, ed. D. J. Pizzarello (Boca Raton: CRC Press), p. 83

Germany, L. M., Reiss, D. J., Sadler, E. S., Schmidt, B. P. & Stubbs, C. W. 1999, ApJ, in press, (astro-ph/9906096)

Glazebrook, K., Abraham, R., Santiago, B., Ellis, R., Griffiths, R., MNRAS, 297, 885

Guzman, R., Gallego, J., Koo, D.C., Phillips, A.C., Lowenthal, J.D., Faber, S.M., Illingworth, G.D., Vogt, N.P. & Nicole, P. 1997, ApJ, 489, 559

Heiles, C. 1979, ApJ, 229, 533

Hogg, D.W. & Fruchler, A.S. 1999, ApJ, 502, 54

Hughes, D. H., Serjeant, S., Dunlop, J., Rowan-Robinson, M., Blain, A., Mann, R. G., Ivison, R., Peacock, J., Efstathiou, A., Gear, W., Oliver, S., Lawrence, A., Longair, M., Goldschmidt, P., & Jenness, T. 1998 Nature, 394, 241

Jones, R.H., Lee, T., Connolly, H.C., Love, S.G., and Shang, H. 2000, in Protostars & Planets IV, ed., in press

Kim, S.Y., Mac Low, M.-M., & Chu, Y.-H. 1999, Bull. AAS, 194,

Kim, S., Staveley-Smith, L., Dopita, M. A., Freeman, K. C., Sault, R. J., Kesteven, M. J. & McConnell, D. 1998, ApJ, 503, 674

Krumholz, M., Thorsett, S.E., & Harrison, F.A. 1998, ApJ, 506, L81

Kumar, P. 1999, ApJ, 523, L113

Kumar, P. & Piran, T. 1999, ApJ, submitted, (astro-ph/9909014)

Lilly, S.J., LeFevre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1

Loeb, A. & Perna, R. 19998, ApJ, 503, L35

Loveday, J. 1997, ApJ, 489, L29

Loveday, J. 1999, in Dwarf Galaxies and Cosmology, Proceedings of the XVIII Moriond Meeting (Paris: Editions Frontieres), in press

MacFadyen, A. & Woosely, S. E. 1999, ApJ, 524, 262

Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M. Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388

Marinoni, C., Monaco, P., Giuricin, G., & Costantini, B. 1999, ApJ, 521, 50

McBreen, B. & Hanlon, L. 1999, A&A, submitted, (astro-ph/9908232)

Minton, K.W. 1994, Mol. Biology, 13, 9

Oey, M. S. & Clarke, C. J. 1997, MNRAS, 289, 570

Pascarelle, S.M., Lanzetta, K.M., & Fernandez-Soto, A. 1998, ApJ, 508, L1

Peebles, P. J. E. 1993, Principles of Physical Cosmology, (Princeton: Princeton University Press)

Puche, D,, Westpfahl, D., Brinks, E., & Roy, J.-.R 1992, AJ, 103, 1841

Reichart, D. E. 1999, ApJ, submitted, (astro-ph/9906079)

Rhode, K. L., Salzer, J. J., Westpfahl, D. J., Radice, L. A. 1999, AJ, 118, 323

Rubin, A.E. & Krot, A.N. 1996, in Chondrules and the Protoplanetary Disk, ed. R.H. Hewins, R.H. Jones, & E.R.D. Scott, (Cambridge: Cambridge Univ. Press), p. 173

Ruderman, M. A. 1974, Science, 184, 1079

Scalo, J. 1998, in The Stellar Initial Mass Function, Proc. 38th Herstmonceux Conference, ed. G. Gilmore, I. Parry, & S. Ryan, p. 201

Schmidt, M. 1999, ApJ, 523, L117

Schneider, S.E., Spitzak, J.G., & Rosenberg, J.L. 1999, ApJ, 507, L9

Sprayberry, D., Impey, C. D., Irwin, M. J., & Bothun, G. D. 1997, ApJ, 482, 104

Staveley-Smith, L., Sault, R. J., Hatzidimitriou, D., Kesteven, M. J.; McConnell, D. 1997, MNRAS, 289, 225

Tenorio-Tagle, G. & Bodenheimer, P. 1988, ARAA, 26, 145

Thorsett, S. E. 1995, ApJ, 444, L55

Totani, T. 1999, ApJ, 511, 41

Tresse, L. & Maddox, S.J. 1998, ApJ, 495, 691

Twarog, B. A. & Wheeler, J. C. 1982, ApJ, 261, 636

van der Schans, G.P. 1991, in The Early Effects of Radiation on DNA, ed. E. M. Fielden & P. O'Neill (NY: Springer-Verlag), p. 347

van Paradijs, J. 1999, Science, 286, 693

Walter, F. 1999, PASA, 16, 106

Walter, F. & Brinks, E. 1999, AJ, 118, 273

Wang, Q. D. 1999, ApJ, 517, L27

Wheeler, J. C. 1999, in Proceedings of the Space Telescope Science Institute Colloquium on Supernovae and Gamma-Ray Bursts, eds. M. Livio, K. Sahu & N. Panagia, in press (astro-ph/9909096)

Wheeler, J.C., Yi, I., Höflich, P., & Wang, L. 1999, ApJ, in press

Wijers, R.A.M.J., Bloom, J.S., Bagla, J.S., & Natarajan, P. 1998, MNRAS, 294, L13

Wilcots, E. M. & Miller, B. W. 1998, AJ, 116, 2363

Wilson, J.W., Townsend, L.W., Schimmerling, W., Khandelwal, G.S., Khan, F., Nealy, J.E., Cucinotta, F.A., & Norbury, J.W. 1993, in Biological Effects and Physics of Solar and Galactic Cosmic Radiation, Part B, ed. C.E. Swenberg, G. Horneck, & E.G. Stassinopoulos (NY: Plenum Press), p. 187

Yan, L., McCarthy, P.J., Freudling, W., Teplitz, H.I., Malumuth, E.M., Weymann, R.J., & Malkan, M.A. 1999, ApJ, 519, L47

Zucca, E. et al. 1997, A&A, 326, 477

Table 1. Properties of Gamma-Ray Bursts

Case	$Q^{(a)}$	r_0	$< L_{peak} >$	${S_{MW}}^{(b)}$	$S_{MW} < L_{peak} > \Delta t$
	10^{51} erg s^{-1} Gpc^{-3} yr^{-1}	Gpc^{-3} yr^{-1}	10^{51} erg s^{-1}	10^{-15} pc^{-2} yr^{-1}	10^{37} erg pc^{-2} yr^{-1}
No evol.	6.3	6.6	0.90	18	1.7
Intermediate evol.	3.8	3.6	1.1	9.4	1.0
Strong evol.	1.3	0.5	2.5	1.3	0.46

[a]All energies and luminosities refer to the 10–1000 keV range.

[b]Rate scaled to the Milky Way using $S_{MS}, L_{peak}\Delta t = Q\Sigma_{B,MS}\Delta t/J_{gal}$. See text.