1. INTRODUCTION

The detection of X-ray, optical, and radio afterglows from gamma-ray burst events (Costa et al. 1997; van Paradijs et al. 1997; Sahu et al. 1997; Frail et al. 1997) and concomitant redshifts (Metzger et al. 1997; Kulkarni et al. 1998a) has provided strong support for the cosmological origin of the phenomenon. The success of the fireball model (Cavallo & Rees 1978; Rees & Mészáros 1992; Mészáros & Rees 1993) is largely independent of the origin of the energy, requiring only an energetic and baryon-poor event confined to small scales, thereby giving rise to a relativistic and optically thick outflow. These requirements alone place extreme limits on the nature of the origin: for the energy ($\sim 10^{52}$ ergs) and scales ($\sim 10^6$ cm), which suggest some catastrophic event associated with the birth or death of compact objects.

Although these are powerful constraints, they leave sufficient leeway to provide several avenues of investigation, such as binary mergers involving neutron stars and black holes (Paczynski 1986; Eichler et al. 1989; Paczyński 1991), failed supernovae collapsing to black holes (Woosley 1993), the collapse of rotating massive stellar cores (“hypernovae”) (Paczynski 1998), or the accretion-induced collapse of white dwarfs or neutron stars in binaries (Usov 1992; Qin et al. 1998). All except Usov’s scenario are “prompt” in the sense that the delay between a burst of star formation and the occurrence of such events is small relative to cosmological timescales. This holds true even for the binary inspiral scenarios, although they may possess a long-timescale tail in the delay distribution (Tutukov & Yungelson 1994; Portegies Zwart & Spreeuw 1996). This trend has spawned investigations of the redshift distribution assuming rates derived from the recently determined cosmological star formation rates (Totani 1997; Wijers et al. 1998).

In this Letter, we propose that many gamma-ray bursts may arise from the collapse of neutron stars to black holes, which triggers a collapse or mergers with less evolved stars. This scenario represents a cosmological history qualitatively different from most previous theories because it contains a significant contribution from an old stellar population, namely the globular clusters. Furthermore, the gas-poor central regions of globular clusters provide an ideal environment for the generation of the recently confirmed afterglows via the fireball scenario. Collisions in close binaries resulting from neutron star birth kicks may also contribute to the overall rate and should lead to associations between some gamma-ray bursts and supernovae of Type Ib/c.

Subject headings: Galaxy; evolution — gamma rays: bursts — globular clusters: general — stars: neutron — supernovae: general

GAMMA-RAY BURSTS FROM STELLAR COLLISIONS

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ABSTRACT

We propose that the cosmological gamma-ray bursts arise from the collapse of neutron stars to black holes, which is triggered by collisions or mergers with less evolved stars. This scenario represents a cosmological history qualitatively different from most previous theories because it contains a significant contribution from an old stellar population, namely the globular clusters. Furthermore, the gas-poor central regions of globular clusters provide an ideal environment for the generation of the recently confirmed afterglows via the fireball scenario. Collisions in close binaries resulting from neutron star birth kicks may also contribute to the overall rate and should lead to associations between some gamma-ray bursts and supernovae of Type Ib/c.

In § 2 we describe the manner in which stellar collisions arise, both in globular clusters and in younger populations. Section 3 provides estimates for the event rates, and § 4 estimates the cosmological evolution of the gamma-ray burst rate in this scenario.

2. COMPACT OBJECTS AND STELLAR COLLISIONS

The salient feature of globular clusters that makes them attractive for our purposes is the greatly enhanced probability of compact object recycling because of the large central densities and high probability of stellar interaction. The strongest empirical evidence of this is the high rate of occurrence of recycled millisecond pulsars in globular clusters relative to the Galactic disk (e.g., Taylor, Manchester, & Lyne 1993), despite the greater difficulty of detection. This is believed to result from exchanges of neutron stars into binaries or close tidal encounters between a neutron star and a main-sequence star (e.g., Hut et al. 1992), following which mass transfer from the newly acquired companion spins the neutron star up to its observed period.

The existence of millisecond pulsars is empirical evidence that such events occur at significant rates. Theoretical investigations of the cross sections for these processes and their applications to typical cluster cores (Davies & Benz 1995; Sigurdsson & Phinney 1995; Davies & Hansen 1998) suggest that the production of these binaries also results in merged systems (“smothered neutron stars”) at rates equal to or greater than the binary production rate. The fate of these systems is much less certain. Depending on the angular momentum of the encounter, the neutron star may spiral to the center of the collision remnant or it may disrupt the star, forming a thick accretion torus (Davies, Benz, & Hills 1992; Rasio 1993).

The limiting accretion rate onto a neutron star is considerably larger than the Eddington rate because of neutrino losses (Zeldovich, Ivanova, & Nadezhin 1972; Chevalier 1993; Fryer, Benz, & Herant 1996), so that the formation of such merged systems is likely to lead to rapid accretion of the disrupted companion material on approximately free-fall times for quasi-spherical remnants and global viscous transport times for disks (Chevalier 1993). The rapid accretion of most of the remnant mass will lead to a collapse to a black hole. This final stage
is reminiscent of several proposed gamma-ray burst scenarios (Woosley 1993; Paczyński 1998; Qin et al. 1998).

Thus, we suggest that the production of stellar-mass black holes is an inevitable consequence of the production of millisecond pulsars in globular clusters (the essential difference in the two outcomes is the rate of accretion, the latter case being regulated by the relatively miserly donation rate of the binary companion). The resultant rapid energy release on small scales is similar to several gamma-ray burst scenarios. However, it represents a formation history qualitatively different from most other proposed scenarios, since it is not tied directly to the star formation rate.

Younger stellar populations in galactic disks have much lower densities, and thus the three-body encounter rate is negligible. Nevertheless, many supernova progenitors are found in binaries, and the evidence is mounting that neutron stars acquire significant velocities at birth (e.g., Lyne & Lorimer 1994; Cordes, Romani, & Lundgren 1993). If the velocity is directed at a binary companion, the resulting stellar collision may produce a similar burst event. Although such an occurrence is a priori unlikely, the gamma-ray bursts are themselves rare events, and we shall show that this rate may be significant.

3. RATES

If we adopt the position that such stellar collapses occur and give rise to gamma-ray bursts, we are still left with the requirement that they produce a significant rate. Canonical rates for cosmological gamma-ray burst production are often based on the estimated rate of binary neutron star mergers (Phinney 1991; Narayan, Piran, & Shemi 1991), about one event per Myr per galaxy and in agreement with fits to the log N - log P relation for nonrelativistic neutron star collisions (Fenimore & Bloom 1995). However, recent analyses of the latter type, using rates based on cosmological star formation histories (as befits the prompt burst production scenarios), have found rates lower than this by factors of ~100 (Wijers et al. 1998) to ~1000 (Totani 1997). Thus, any rate in the range of 10⁻³ to 1 Myr⁻¹ per galaxy is of significance.

The rate of stellar collisions increases dramatically with central cluster density, and thus the total rate will be dominated by those clusters that are undergoing the “binary burning” phase thought to provide support against core collapse (e.g., Goodman 1988). Indeed, many millisecond pulsars are found in post-core-collapse clusters such as M15 or in the highest density noncollapsed clusters such as 47 Tuc.

Burst rate estimates based on theoretical cross sections and globular cluster evolution are model dependent, but we may obtain robust empirical estimates with the modest assumption that the burst rate is comparable to or larger than the rate of millisecond pulsar production (see § 2). The pulsar birthrate may be estimated by considering the characteristic spin-down ages of the individual pulsars and the selection effects involved in the detections. Phinney (1996) estimates that density-dependent production rates of 10⁻⁸, 2 × 10⁻⁹, and 5 × 10⁻¹⁰ yr⁻¹ in individual clusters of central luminosity density 10⁶, 10⁷, and 10⁸ L☉ pc⁻³, respectively. Note that these refer only to currently observable pulsars and are thus almost certainly lower limits, given the steepness of the disk pulsar luminosity function and the large distances to globular clusters. Phinney estimates that the true rate could be ~100 larger. Assuming ~20% of the globular clusters in the galaxy have sufficiently high central densities (Djorgovski & King 1986; Chernoff & Weinberg 1990), this means the event rate for our Galaxy can lie anywhere in the range 10⁻² to 10 Myr⁻¹. Hence, relative to the new lower rates inferred by Totani (1997) and Wijers et al. (1998), the globular clusters are almost certainly important.

The contribution from the Galactic disk will be dominated by close binaries. The supernovae that occur in such systems appear as Type Ib/c at a rate ~10⁻⁷ yr⁻¹, and studies of low-mass X-ray binary formation suggest presupernova separations of ~10–25 R☉ (e.g., Kalogera & Webbink 1998). Assuming randomly directed kicks from the supernova, the collision rate (for companions of approximately solar mass) is ~1 Myr⁻¹ in our Galaxy. Hence, this pathway may also be important.

4. COSMOLOGICAL EVOLUTION

A gamma-ray burst history dominated by globular cluster production will provide a cosmological history qualitatively different from the currently fashionable one based on star formation rate. Although the epoch of globular cluster formation is somewhat theory dependent (see Fall & Rees 1988 for a review), globular cluster ages (Chaboyer, Demarque, & Sarajedini 1996) suggest that a significant fraction of the Galactic system must have existed since high redshifts.

To illustrate the cosmological history of globular cluster burst production, we have calculated the evolution of a globular cluster population assumed to have formed in a single burst 15 Gyr ago. Following Murali & Weinberg (1997), we assume 250 clusters with an initial mass distribution dN/dM ∝ M⁻¹.⁷-five in the mass range 10⁴–10⁶ M☉ and a spatial distribution of ρ ∝ R⁻².⁷-five in a Milky Way–like galaxy. Individual clusters are evolved using the Fokker-Planck models of Murali & Weinberg (1997) on circular orbits in the spheroidal potential. Extra heating due to eccentric orbits and the disk potential do not change the evolution qualitatively. Figure 1 shows the evolution of total integrated core mass in regions of density above the threshold (taken to be 10³ M☉ pc⁻³) in the cluster system as a function of time. The initial rise comes from low-mass clusters at small radii (which are the dominant population and

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**Fig. 1.** Evolution of the integrated mass in regions above a critical density 10⁻³ M☉ pc⁻³ for an entire galactic globular cluster system. The rate of stellar collisions should evolve in a similar fashion.
which have the shortest evolutionary timescale). Eventually the integrated core mass drops again as the low-mass clusters evaporate completely. Although a galaxy globular cluster system is influenced by environment (e.g., cD galaxies such as M87 have much larger globular cluster systems), the number of clusters per galaxy scales roughly with luminosity within a given Hubble type (Harris & Racine 1979; van den Berg 1984; Harris 1991). Thus, for the illustrative discussion below, we will adopt our above rate as a function of time per galaxy for all types (since spiral and elliptical galaxies have similar numbers of clusters on average) and simply normalize to galactic luminosity densities.

Figure 2 shows the log \( N \)-log \( P \) relation from the BATSE 3B catalog (Meegan et al. 1996) for the 1024 ms channel. The fit is for peak fluxes \( P > P_\text{th} = 0.4 \text{ photons cm}^{-2} \text{ s}^{-1} \) and assuming a single, standard candle luminosity and the cosmological history determined above. The threshold redshifts for currently favored open and \( \Lambda \) models (see Ostriker & Steinhardt 1995) lie in the range 2.5–5 depending on the assumed spectral index, taken to be \( \alpha = 1.1 \pm 0.3 \) (Mallozzi, Pendleton, & Paciesas 1996). The derived isotropic standard candle luminosities are \( \sim 5 \times 10^{52} \text{ ergs} \). The required rate, using the estimated globular cluster comoving space density \( \sim 10 h^3 \text{ Mpc}^{-3} \) (Phinney 1991), is then only \( 3 \times 10^{-9} \text{ yr}^{-1} \) per globular cluster. When this average is only taken over those undergoing core collapse, then the inferred rates are similar to the low end estimated in § 3. Totani (1997) finds that simple comparisons like this one, but using rates based on empirical star formation laws, are improved by an additional contribution from high redshifts, which he attributes to an early epoch of elliptical galaxy formation. Globular cluster contributions can serve this purpose equally well. The true rate is likely to be a combination of this one and one that does follow the star formation rate if the contribution from close helium star binaries is important. Indeed, despite the very different conceptual histories, the globular cluster and star formation burst rates display similar redshift dependences, since both increase monotonically for several gigayears and then fall away at later times.

5. CONSEQUENCES AND CONCLUSIONS

The gamma-ray burst scenario described here resembles other mechanisms in terms of physical processes but contains an important difference with respect to most other cosmological gamma-ray burst models, namely a significant contribution from old stellar populations. As such, afterglow searches should be able to distinguish between this and other models by identifying host galaxies. Most of the currently accepted burst models suggest that afterglows should be associated with galaxies undergoing vigorous star formation, while our scenario will produce afterglows associated with galaxies across the Hubble sequence.

A particularly attractive feature of the globular cluster contribution is that it provides a naturally gas-poor environment for the fireball to propagate. Although the high stellar density implies that \( \sim 10^5 M_\odot \) of material should be deposited in the cluster cores from giant star mass loss between galactic disk passages, observations indicate that globular cluster cores are remarkably gas poor (see Roberts 1988; Knapp et al. 1996 for reviews). Typical upper limits are \( \sim 0.1–1 M_\odot \) in total. IRAS measurements (Origlia, Ferraro, & Fusi Pecci 1996) infer warm dust masses of \( \sim 10^{-8} \) to \( 10^{-6} M_\odot \) (implying gas masses \( \sim 100 \) times larger). Furthermore, they present evidence that this is concentrated in unresolved circumstellar envelopes, so that average intracluster values are even lower. Explanations range from ram pressure stripping and photoionization (see above reviews) to evacuation due to the accumulated wind from millisecond pulsars (Spergel 1991). Thus, ambient gas masses of \( \sim 10^{-5} M_\odot \) on scales \( \sim 0.1–1 \) pc are generic, making globular cluster cores an ideal environment for the creation of gamma-ray bursts and their afterglows from fireball models.

Gamma-ray bursts associated with post-supernova collisions in binaries may also be identifiable. While not wishing to adopt any particular model for burst evolution, we note that gamma-ray bursts in these events should be associated with Type Ib/c supernovae (which provide the supernova kick).

In addition to the possible link to gamma-ray bursts, the production of black holes described in this Letter is interesting in its own right. The presence of stellar mass black holes resulting from very massive stars (Larson 1984; Kulkarni, Hut, & McMillan 1993; Sigurdsson & Hernquist 1993) has profound consequences for globular cluster structure and evolution by virtue of their larger masses and greater central concentration. The black hole population we describe differs from the prior hypotheses because it is not a product of initial conditions but rather a product of cluster evolution and stellar interaction. The final population will be determined by the competition between the production and depletion via mass segregation and dynamical ejections. Elucidation of this process may allow us to place constraints on this scenario from the apparent paucity of black hole X-ray binaries in globular clusters (in’t Zand et al. 1998).

In conclusion, we have proposed that the processes that produce millisecond pulsars in globular clusters also produce a significant population of stellar-mass black holes and may provide the source of gamma-ray bursts. In particular, the propagation of a fireball is aided by the evacuated nature of cluster cores, possibly by the millisecond pulsar winds themselves. The fact that these bursts arise from an old stellar population suggests a significant contribution from high redshifts, an assertion that is testable with detailed monitoring of the optical afterglows. The equivalent mechanism in younger stellar pop-
ulations should lead to an association of some bursts with Type Ib/c supernovae.

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