A Century of Gamma Ray Burst Models

More than 100 gamma-ray burst progenitor models have now been published in refereed journals. A list of the models published before the end of 1992 is presented and briefly discussed. The consensus of the present astronomical community remains that no specific model is particularly favored for cosmic bursts. Recent BATSE results make most of these models untenable in their present form, opening up the field to another era of speculative papers. Is speculation in this area becoming valueless? Alternatively, one may argue that the new data make many of the old models untenable, and simply adapting old models may not be sufficient. With this in mind, three relatively unexplored "toy" paradigms are suggested from which more detailed models for the progenitors of gamma-ray bursts may be made.

Key Words: *gamma-ray bursts*

"For theorists who may wish to enter this broad and growing field, I should point out that there are a considerable number of combinations, for example, comets of antimatter falling onto white holes, not yet claimed."

—M. Ruderman[1]

1. INTRODUCTION

Gamma-ray bursts (GRBs), discovered 25 years ago,[2] remain one of the biggest mysteries in modern astronomy. No theoretical model explaining GRBs has gained general acceptance, although now more than 100 have been proposed in the refereed literature. Is speculation in this field becoming valueless? Is there any value to

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past speculative models that no longer can be considered reasonable GRB models in light of present data?

A list of the more than 100 papers suggesting GRB progenitor models, or variants thereof, is given in Table I. A paper will appear on this list if it was published in a refereed journal, appeared before the end of 1992, and proposed a new revised model for the origin of a GRB. A reasonable effort was made to make Table I complete; however, it is probable that several papers were missed. A conscious subjective decision *not* to include a paper might have been made if it was deemed that the paper did not create a significantly new progenitor model or did not add significantly to any existing progenitor model (the paper might still be an excellent scientific paper, however). A paper might also have been excluded if it focussed specifically on the physics of a potential mechanism rather than suggesting a significantly different type of mechanism. Papers appearing in journals less circulated in the United States might also have been missed. Please note that the numbers of references in Table I are different from the reference numbers of papers cited in the reference section at the end of this paper.

Table I is divided into 8 columns. The first column gives a model reference number. Models are listed in chronological order of the date they were received by the journals. In the case of two models received on the same day, the model that was published first is listed first.

Column two lists the lead author. If there were two or more authors, an "et al." is given following the first author. Column 3 lists the year the article was published. Column 4 lists the reference in a compact form. Most of these conform to the accepted modern format; however, several non-standard abbreviations were made, primarily due to space limitations. Specifically, "CJPhys" refers to the Canadian Journal of Physics, "CosRes" refers to Cosmic Research, "PRL" refers to Physical Review Letters, and "SovAstron" refers to Soviet Astronomy.

Column 5 lists the major progenitor body involved in the GRB model. Many abbreviations are straightforward, with "NS" meaning neutron star, "WD" meaning white dwarf, "BH" meaning black hole and "AGN" meaning active galactic nucleus. Less standard abbreviations are: "CS" meaning cosmic strings, "DG" meaning dust grain, "GAL" meaning external galaxy, "MG" meaning magnetic reconnection, "RE" meaning relativistic electrons, "SS" meaning strange star, "ST" meaning normal star, and "WH" meaning white hole.

If a second body is involved in the GRB model, it is listed in column 6, even if it cannot be clearly labelled as a body. The following additional abbreviations were used: "AGN" meaning active galactic nucleus, "AST" meaning asteroid, "COM" meaning comet, "ISM" meaning interstellar medium, "MBR" meaning microwave background, "PLAN" meaning planet, and "SN" meaning supernova shock.

Column 7 lists the location of the GRB explosion. Here "COS" refers to a cosmological setting, "DISK" refers to the disk of our Milky Way Galaxy, "HALO" refers to the halo of our Galaxy, and "SOL" refers to the outer solar system. In cases where the GRB location was not well specified between the Galactic disk and the Galactic halo, the latter location was typically chosen if energy constraints allowed.

Column 8 gives a brief description of the model (or refinement) proposed. I apologize for the gross generalizations made here and for any inaccuracies. Several times terms and abbreviations are used in the description that need explanation, and I must ask the reader to consult the papers cited for this explanation. Happily, I was not shaken from my belief that once terms are defined, the gist of any good scientific paper can be summarized in five words or less. (Admittedly this makes a better parlor game than a truism.)

The first entry in Table I requires explanation. The prime reason the GRB discovery paper[2] gives for the initial search was to test the prediction of GRB existence made by Colgate in Ref. 1 of Table I. GRBs were discovered in this search but found *not* to be coincident with observed supernovae in local galaxies, as this Colgate model predicts. However, since this Colgate paper gave a model for GRBs which fostered GRB detection, it is arguably the first GRB model, even though it predates their detection.

Inspection of Table I shows several interesting trends. First of all, most of the models are based in the Galactic disk, and most are based on neutron stars. The most diverse group of models was published immediately after the discovery of GRBs, but over the years a wide variety of distinctly different models have been published. Based on the publication record, it appears that the com-

TABLE I

Model #	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap&SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flares on nearby stars
12.	Shklovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Shklovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap&SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap&SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap&SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 256, 112	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap&SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugan	1976	Ap&SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag gating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap&SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares

32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap&SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap&SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al.	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap&SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap&SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot synch e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap&SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Shklovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap&SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap&SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm. of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap&SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e+/- opt thk plasma outflow indicated
69.	Bisnovatyi- et al.	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahai et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare

TABLE I (*Continued*)

Model #	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic
75.	Curtis	1988	ApJ, 327, L81	WD		COS	WD collapses, burns to form new class of stable particles
76.	Melia	1988	ApJ, 335, 965	NS		DISK	Be/X-ray binary sys evolves to NS accretion with recurrence
77.	Ruderman et al.	1988	ApJ, 335, 306	NS		DISK	e+/- cascades by aligned pulsar outer-mag-sphere reignition
78.	Paczynski	1988	ApJ, 335, 525	CS		COS	Energy released from cusp of cosmic string (revised)
79.	Murikami et al.	1988	Nature, 335, 234	NS		DISK	Absorption features suggest separate colder region near NS
80.	Melia	1988	Nature, 336, 658	NS		DISK	NS + accretion disk reflection explains GRB spectra
81.	Blaes et al.	1989	ApJ, 343, 839	NS		DISK	NS seismic waves couple to magnetospheric Alfen waves
82.	Trofimenko et al.	1989	Ap&SS, 152, 105	WH		COS	Kerr-Newman white holes
83.	Sturrock et al.	1989	ApJ, 346, 950	NS		DISK	NS E- field accelerates electrons which then pair cascade
84.	Fenimore et al.	1988	ApJ, 335, L71	NS		DISK	Narrow absorption features indicate small cold area on NS
85.	Rodrigues	1989	AJ, 98, 2280	WD	WD	DISK	Binary member loses part of crust, through L1, hits primary
86.	Pineault et al.	1989	ApJ, 347, 1141	NS	COM	DISK	Fast NS though Oort clouds, fast WD bursts only optical
87.	Melia et al.	1989	ApJ, 346, 378	NS		DISK	Episodic electrostatic accel and Comp scat from rot high-B NSs
88.	Trofimenko	1989	Ap&SS, 159, 301	WH		COS	Different types of white, "grey" holes can emit GRB
89.	Eichler et al.	1989	Nature, 340, 126	NS	NS	COS	NS - NS binary members collide, coalesce
90.	Wang et al.	1989	PRL, 63, 1550	NS		DISK	Cyclo res & Raman scat fits 20, 40 keV dips, magnetized NS
91.	Alexander et al.	1989	ApJ, 344, L1	NS		DISK	QED mag resonant opacity in NS atmosphere
92.	Melia	1990	ApJ, 351, 601	NS		DISK	NS magnetospheric plasma oscillations
93.	Ho et al.	1990	ApJ, 348, L25	NS		DISK	Beaming of radiation necessary from magnetized neutron stars
94.	Mitrofanov et al.	1990	Ap&SS, 165, 137	NS	COM	DISK	Interstellar comets pass through dead pulsar's magnetosphere
95.	Dermer	1990	ApJ, 360, 197	NS		DISK	Compton scattering in strong NS magnetic field
96.	Blaes et al.	1990	ApJ, 363, 612	NS	ISM	DISK	Old NS accretes from ISM, surface goes nuclear
97.	Paczynski	1990	ApJ, 363, 218	NS	NS	COS	NS-NS collision causes v collisions to drive super-Ed wind
98.	Zdziarski et al.	1991	ApJ, 366, 343	RE	MBR	COS	Scattering of microwave background photons by rel e-s
99.	Pineault	1990	Nature, 345, 233	NS	COM	DISK	Young NS drifts through its own Oort cloud
100.	Trofimenko et al.	1991	Ap&SS, 178, 217	WH		HALO	White hole supernova gave simul burst of g-waves from 1987A
101.	Melia et al.	1991	ApJ, 373, 198	NS		DISK	NS B- field undergoes resistive tearing, accelerates plasma
102.	Holcomb et al.	1991	ApJ, 378, 682	NS		DISK	Alfen waves in non-uniform NS atmosphere accelerate particles
103.	Haensel et al.	1991	ApJ, 375, 209	SS	SS	COS	Strange stars emit binding energy in grav. rad. and collide
104.	Blaes et al.	1991	ApJ, 381, 210	NS	ISM	DISK	Slow interstellar accretion onto NS, e- capture starquakes result

105.	Frank et al.	1992	ApJ, 385, L45	NS		DISK	Low mass X-ray binary evolves into GRB sites
106.	Woosley et al.	1992	ApJ, 391, 228	NS		HALO	Accreting WD collapses to NS
107.	Dar et al.	1992	ApJ, 388, 164	WD		COS	WD accretes to form naked NS, GRBs, cosmic rays
108.	Hanami	1992	ApJ, 389, L71	NS	PLAN	COS	NS - planet magnetospheric interaction unstable
109.	Meszaros et al.	1992	ApJ, 397, 570	NS	NS	COS	NS - NS collision produces anisotropic fireball
110.	Carter	1992	ApJ, 391, L67	BH	ST	COS	Normal stars tidally disrupted by galactic nucleus BH
111.	Usov	1992	Nature, 357, 472	NS		COS	WD collapses to form NS, B-field brakes NS rotation instantly
112.	Narayan et al.	1992	ApJ, 395, L83	NS	NS	COS	NS - NS merger gives optically thick fireball
113.	Narayan et al.	1992,	ApJ, 395, L83	BH	NS	COS	BH-NS merger gives optically thick fireball
114.	Brainerd	1992	ApJ, 394, L33	AGN	JET	COS	Synchrotron emission from AGN jets
115.	Meszaros et al.	1992	MNRAS, 257, 29P	BH	NS	COS	BH-NS have νs collide to γs in clean fireball
116.	Meszaros et al.	1992	MNRAS, 257, 29P	NS	NS	COS	NS-NS have νs collide to γs in clean fireball
117.	Cline et al.	1992	ApJ, 401, L57	BH		DISK	Primordial BHs evaporating could account for short hard GRBs
118.	Rees et al.	1992	MNRAS, 258, 41P	NS	ISM	COS	Relativistic fireball reconverted to radiation when hits ISM

munity had generally settled on the idea of Galactic disk neutron star progenitors in the 1980s, as the majority of papers published then were refinements of this idea (with a few very notable exceptions). Any settling that might have occurred then became unsettled with the announcement of the first BATSE results in September 1991.

Launched in April of 1991, the *Compton* Gamma Ray Observatory incorporated an instrument specifically designed to detect and measure GRBs: the Burst and Transient Source Experiment (BATSE). In September of 1991 at The Compton Observatory Science Workshop[3] in Annapolis, Maryland, the BATSE team, headed by Dr. Gerald Fishman, briefly summarized the results of the first few months of BATSE observations. These results shook gamma-ray burst understanding to the core. They showed that BATSE had so far measured an angularly isotropic GRB distribution, and that the brightness distribution (sometimes called "log N–log S") was not uniformly a $-3/2$ power law. Although this data were not in conflict with previous data, most scientists and scientific modeling had predicted an angular distribution in which the galactic plane was visible, and, barring this, a continuation of the $-3/2$ power law results. These results were first published in a paper sent to Nature.[4]

The result of this announcement was a dramatic shift in GRB modeling. Papers submitted in 1992 were, for the first time, predominantly cosmologically placed. There was also a slight shift away from neutron star progenitor models, although NS models still outnumbered all other models combined.

The GRB progenitor problem is now arguably the most prolific in astronomical history, easily surpassing the pulsar problem in this area.[5] (For a list of potential pulsar progenitor models, which numbered 20 about 3 years after their discovery, see Table 2 of Ref. 5. Even at this early date, though, there was a very strong community sentiment toward rotating neutron stars.) Reasons for this include the uncertainty of several important data features, the relatively long period of speculation, the relatively large amount of data needed to solve the dilemma compared to the amount of data taken, the relatively large numbers of astronomers and astronomical journals in the world today, the relative ease which word processing makes published speculation possible, and the pressure to publish in today's academic environment, to name a few. Probably the best reason for the proliferation of GRB models, though, is that new data entering the field has not bolstered any specific model (or even setting). The BATSE results, in fact, have made the majority of published models more tenuous. Therefore, in light of this new data, it is possible that even this list of over 100 models lacks diversity.

2. SERENDIPITOUS MODELS

Speculative model building based on reliable data *can* be good science, and should be encouraged so long as it (a) reasonably explains the data, (b) is falsifiable and/or (c) is generally interesting astrophysically in its own right and potentially applicable to areas outside GRBs. Any model that does either (a), (b), or (c) particularly well should be considered by itself meritorious.

There are models or types of speculative modeling that should not be so encouraged. Models that use non-standard physical laws, that incorporate astronomical objects that are not known to exist, or that rely on data that is not well understood should be treated with extra scrutiny. These models should only be proposed if they are particularly falsifiable. Otherwise, even if they are correct, few will believe them.

In every flurry of scientific speculation, inevitably most of this speculation is wrong. However, even if the speculation did not ultimately result in a viable model for the mystery in question, many times the speculation was valuable in its own right. In a way, this is the theoretical equivalent to serendipitous observational discovery.

Is there the potential for theoretical serendipity in speculation on the origins of GRBs? Hopefully there will be numerous examples in the GRB model list. Here two potentially interesting cases are suggested.

The first is that of colliding neutron stars (see Ref. 89 in Table I, and all subsequent references with "NS" listed in both columns 5 and 6). These models may still turn out to be the correct model for GRBs, but even if they are not, they could still be valuable as serendipitous speculation. Neutron star binary systems are known to exist, and the stars are known to be spiraling toward each other while releasing binding energy in the form of gravitational waves.[6] Therefore neutron star--neutron star collisions must happen occasionally—the questions are at what rate and at what visibility. Possibly these collisions would not be observable as classical GRBs, but in other radiations, and with another frequency.

A second case involves models proposed to explain the majority of GRBs may come in useful in understanding a smaller class of similar bursts: soft gamma repeaters (SGRs).[7] Particularly exemplary in this regard might be the models of accretion and thermonuclear detonation on the surface of neutron stars (see Refs. 7 and 27 of Table I, and many subsequent papers). These models generally do not release enough energy to account for cosmic GRBs at cosmological distances, but may release enough energy to explain SGRs.

3. A BIASED GRB MODEL START UP KIT

Why the continued emphasis on neutron star models, particularly in the light of the new data? For one reason, neutron stars still represent active environments where energy fields go to extremes, creating a ripe setting for the powerful explosion that are GRBs. Also, it is a tempting coincidence that if GRBs lie at cosmological distances, the energy released in a GRB (assuming isotropy of the explosion) is a few percent of the binding energy of a neutron star.

One general problem with neutron star models is that they generally liberate most of the energy in neutrinos. To complement such a model, a method of converting a fraction (even 0.1 percent) of the neutrinos into γ-rays must also be found. Several of the most recent models have concerned themselves with this (for example, Ref. 115 of Table I).

No single piece of evidence has been found to suggest neutron stars conclusively as GRB progenitors. Were a rotation period reminiscent of a pulsar found in a GRB light curve, this could be considered conclusive evidence. Therefore, to reflect this lack of evidence, two of the paradigms suggested below are not constrained to neutron star environs.

In generating a model of any type based upon believable data, one must know which data to believe. This is particularly difficult in GRB astronomy, as there is continuing debate as to whether the GRB data show cyclotron lines, annihilation lines, a distribution which is truly isotropic, a duration histogram indicative of one population or two, whether SGRs indicate a separate class or should be grouped with the other GRBs, or whether optical counterparts have ever been seen. As noted above, this diversity may be partially responsible for the large number of GRB models, as a different model is usually needed to explain a different subset of the data.

Deciding which data to believe is implicitly a biased procedure. Therefore, before stating any new idea on origins of GRBs, I state my prejudices explicitly below. Let me start by stating here that I find my biases change in an unscientific manner, depending on how much data I perceive supports a particular bias, the quality and manner this data was taken, the history of a data set, the general biases in the literature, the specific biases of my closer colleagues, and to whom I have listened most recently. The biases listed below are indicative of no one other than myself. Some are more controversial than others.

- SGRs are a different class of GRB and are not to be explained by the cosmic GRB model. (Note that models trying specifically to explain SGRs *are* included in Table I.)

- A model must predict an isotropic but "confined" (log N vs. log S not fully described by a $-3/2$ power law) GRB distribution that is consistent with the current BATSE data.

- A model must predict that each GRB has a somewhat similar spectrum. Generally this means increasing in the hard X-ray, turning over in the early gamma-ray, decreasing power law in the gamma-ray, and turning off in the hard gamma-ray.

- A model geometry must be able to explain the choppy time structure inherent in the data. Therefore I preferred that something during the process should either come in pieces or break up into pieces. This is because the time profiles of GRBs can be quite complicated and composed of many discernible subpulses.[8]

- The GRB process should occur at cosmological distances, and additionally, should be uniformly distributed in the universe. This is because the log N–log S relationship and time-dilation GRB comparisons fit a uniform cosmological distribution quite well.[9–11]
- Neutron star models are to be avoided. Most of the literature is composed of neutron star models, and most probably if GRBs are formed in neutron star environs, one of the existing models already goes most of the way to explaining it. Besides, no convincing periodicities indicative of neutron star rotation have ever been found.
- No antimatter. I feel that there is no strong evidence that a substantial part of the universe is composed of antimatter.
- Relativistic beaming should be a natural consequence of the model.[12] This is to stop γ–γ interactions from degrading the higher energy tail of GRB's spectrum.
- Models should be capable of producing time scales as short as a millisecond and as long as 5 minutes. These roughly correspond to the duration of the longest and shortest GRBs.
- Models should not predict GRB recurrence in the same angular location. GRBs do not recur at the same place in the sky, at least not on the time scale from 10 minutes to a few years. Note, however, that GRBs do show recurrent pulses on the time scale of a few 100s of seconds.

4. THREE MORE PARADIGMS

One might think that with 118 GRB progenitor models in the journals, no more are needed. One may also argue that the new data make many of the old models untenable, and simply adapting old models may not be sufficient. There are many extremely energetic places and phenomena already known in astrophysics and surely many more yet still to be discovered. In this light, it appears that the current GRB model list may not be diverse enough. Many similar models may not be as useful as a few very different ones.

Is it possible to build completely different models and paradigms that fit the data and yet still rely on plausible astronomical settings and established physical laws?

The progenitor paradigms that follow are not well detailed: they are at most toys or outlines from which more elaborate models can be built. I don't fully believe any of them, but there are aspects to each of them I find appealing. They are provided as examples and as "food for thought." My hope is that they will at least foster discussion and more diverse model building.

Lightning

Although there can be many models based on lightning, here is one that tries to be cosmological. Lightning occurs frequently in planetary settings, causing one to wonder how frequently it occurs outside such a setting. Lightning has recently been suggested in a more general astrophysical context.[13]

There is known to be at least a little bit of intergalactic matter in the form of un-ionized baryonic matter, some of which is known to be clumped into higher density clouds.[14] General gravitational settling combined with collisions of material in these clouds could lead to non-negligible E-fields and charge separation. As two sub-clumps pass near each other, a series of lightning bolts could discharge between the two. But here, unlike on Earth, the distance and voltage drop between the clouds would accelerate charged particles to energies where they would beam radiation in the gamma-ray band when they strike the destination cloud(s).

The good points of this paradigm include that it explains naturally the lack of visible objects at GRB locations. The time series of the intensity of terrestrial lightning has similar properties to the time series of intensity of GRBs.

Bad points of this paradigm include that a detailed theory would have to rely on densities of clouds that are not well constrained by measurements, sizes that are not known to several orders of magnitude, and gas and dust properties that are completely unknown. Energy constraints are also too ad-hoc: why wouldn't one get more energetic or less energetic lightning bolts? One must also fine-tune the initial conditions so that there is not too much ionized matter around to damp the charge separation necessary for lightning to be created.

If such a paradigm is correct, there will never be a definitive correlation found between any bright object and a GRB location, no matter the angular precision of the GRB location. There might, however, be a correlation between the magnitude of absorption of QSO light and GRB locations, when GRB locations are known to a few arcseconds or better. A similar but smaller scale lightning effect should occur in stellar neighborhood molecular clouds.

Deflection of AGN Jets

Brainerd (Ref. 114 of Table I) has remarked on the similarity of published models of AGN and the models needed for GRBs. One way to facilitate this is for a comet (for example) to wander into an AGN jet and scatter some of the beam temporarily toward us. Soon the comet melts. Comets are particularly good as deflectors since they may be composed of several pieces, which could give rise to the pulse-composed structure of GRBs.

On the positive side, many of the physical aspects of AGN models that GRB models have in common are naturally explained. The pulse-structure of GRB time series may also be naturally explained by the piecemeal structure of comets. However, one might expect that the total energy deflected by the comets would be widely variable. One might also expect that AGN deflection models would have repeating GRBs, as different comets wander into the same AGN jet. Brighter, longer AGN jets are more likely to cause GRBs, but these are typically more distant, so GRBs would not be uniformly distributed.

Testable predictions of such a model include that when GRBs are better located to an accuracy of better than 10 arcseconds, they should be correlated with AGN positions. Also, GRBs will be seen to occasionally repeat from the same location, but with different light curves.

Mini-Black-Holes Devouring Neutron Stars

Okay, I know I said we don't need more neutron star models but this one was just too much fun. This model was motivated by the ever-so-slim possibility that three major astronomical puzzles could be solved in one fell swoop. Mini-black-holes (mBHs), on the order of a fraction of a solar mass, cannot be excluded, presently, from comprising all the dark matter. A few mBHs could have found their way to the center of the Sun to solve the solar neutrino problem.[15,16] What if one of these mBHs were to fall not into our Sun but into a neutron star instead?[17] One might expect a GRB. As the mBH ate its way through the star the mBH would increase in mass and eat faster. After a while the neutron star would undergo massive restructuring (core quakes) every pass of the mBH through it. The tides of the mBH could also cause explosive decompression on nearer parts of the neutron star. The neutron star could be "eaten" completely on the time scale of a few crossing times of the mBH, or just "bitten" during one mBH unbound pass. Neutron star–mBH collisions are unlikely to occur for uniformly distributed chance encounters in the universe, but could be random collisions in a dense stellar environment (near an AGN, for example), or part of a binary system in a normal galaxy.

On the positive side is the extremely appealing idea that three major astronomical problems could be solved simultaneously. Also, in a gross sense, the energy and timing considerations of this paradigm are roughly okay.

However, the origin of mBHs is unclear at best. Their present existence is unsubstantiated and extremely ad-hoc. One might expect neutron star vibrations or rotation-induced periodicities to be evident in the GRB time series, but they aren't. For lower mass mBHs, the mBH would have to take many passes through the center of the neutron star before it got enough mass to destroy the neutron star. This oscillation time scale should be evident in the GRB, and it isn't. Most of the neutron star binding energy should be liberated in the form of neutrinos—one must still find a way to convert a sizeable portion of the energy to gamma-rays.

Predictions of this paradigm include the fact that strong GRBs should have detectable gravitational wave emissions in the next generation gravitational wave detectors. Also future arcsecond locations of strong GRBs should show correlation with dim galaxies (which might house the neutron stars). General mBH existence should be implied by the neutrino emission of the Sun and the dynamics of some nearby stellar systems.

5. DISCUSSION

I apologize if I have omitted or badly described any models in Table I. I will try to update Table I on a yearly basis, however, and continually honor requests for a photocopy of it. Therefore, I welcome any comments, corrections, or omissions that the reader may have on this table.

It will take more than speculation to solve the current GRB model dilemma—it will certainly take more observations. Clearly, several observational uncertainties need to be resolved for theorists to know which data subsets to believe. Do GRBs show cyclotron lines, annihilation lines, or repetition? These questions should be answered by the current *Compton* mission. Do GRBs show extra X-ray absorption in the galactic plane? Are GRB positions, when known more accurately, correlated with any known object? These are examples of questions which may be answered with the next generation of GRB measuring instruments. If, when these data arrive, they don't bolster an existing model, we may well be in for yet another era of GRB model speculation!

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ROBERT J. NEMIROFF
NASA/GSFC/USRA,
Code 668.1,
Greenbelt, Maryland 20771

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