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The Galactic Model of GRBs

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Abstract. The galactic model of gamma ray bursts (GRBs) is based upon the observed production of soft gamma ray repeaters (SGRs) in our galaxy and the consequences of a reasonable model to explain them. In this view GRBs are the long term result of the burn-out conditions of the SGRs in this and in other galaxies. A delay of ~ 30 million years before GRBs are being actively produced can be understood as the time required for the ejected matter during the SGR phase to cool, condense, and form planetesimals that are eventually captured by the central neutron star. The amount of disk matter and the interaction between each GRB and the disk determine the rate of burst production and turn-off time of GRBs. The x-ray afterglow as well as optical emission is derived from x-ray fluorescence and ionization of previously ablated matter.

INTRODUCTION

The primary motivation for considering GRBs to originate at cosmological distances has been the extraordinary isotropy measured by BATSE of all bursts. This has then been reasonably interpreted by the "cosmologically inclined community" as "only the universe could be that isotropic!". However, this simplistic view is not the case in the event that GRBs originate from fast objects ejected from our galaxy (and from all other galaxies as well) [1,2]. It is rather surprising to realize that the acceptable parameter space delineated by Bulik, Coppi, and Lamb from fitting the BATSE data is so large and overlaps the conditions predicted by the present model, based upon fast neutron stars and planetesimal accretion [3,4]. This parameter space is bounded by three conditions: 1) the ejection velocity of neutron stars must be $\gtrsim 800$ km/s and $\lesssim 1500$ km/s in order to diminish galactic gravitational distortion and not approach M31 too closely; 2) the turn-on time should be within $3 - 5 \times 10^7$ y, long enough so that the first bursts are far enough away from both us and the center of the galaxy; and 3) the turnoff time $\sim 5 \times 10^8$ y, permitting averaging over a galactic rotation period and excluding M31.

The starting point of the model is that GRBs are the result of the expected evolution of the burn-out conditions of SGRs (see also [5]). During the SGR phase, the thickness of the captured disk of matter decreases due to both accretion and ablation (from SGRs) until the disk is too thin to support the alpha viscosity accretion mechanism. The resulting quiescent disk then evolves to planetesimals, which are then scattered into neutron stars producing GRBs. The formation of planetesimals accounts for the delayed turn-on of GRBs, exactly as in planet formation within the solar system.

SGRS

A sizable amount of matter ($\sim 1-10\% M_\odot$) will be captured by the high velocity neutron star in a near-miss collision with its companion [4]. This matter forms a thick accretion disk which subsequently evolves both radially outward and inward, accreting a fraction onto the central neutron star, i.e., the SGR phase. The total energy emitted during the SGR phase is $\sim 10^{47}$ ergs (the total mass required is $\sim 10^{27}$ g), mostly from steady, soft x-ray emission at $\sim 3 \times 10^{35}$ ergs/s and a fraction from the SGRs themselves. The steady accretion is at the Eddington limit corresponding to the enhanced iron-like element opacity ($\sim 10^3\times$ Compton opacity). SGRs are from the episodic high state accretion of ionized plasma that is so thick, $\gtrsim 10^4$ g cm^{-2} as to be self-shielded against radiation pressure, hence, leading to episodes of much larger luminosities than the above Eddington limit.

The x-ray flux of an SGR event terminates the inner disk mass inflow by ablation so that a subsequent period of mass replenishment from outer radii requires ~ 10 revolutions at a fraction of an AU, i.e., a year or so between bursts. Each SGR event will ablate roughly 10 g cm^{-2} of matter out to at 1AU, $\sim 10^{27}$ g per year or 10^{31} g total. This large mass in Keplerian orbit is thick enough to sustain $\sim 10^4$ events until the residual thickness is $\lesssim 100$ g cm^{-2}. This is the critical thickness necessary to contain heat (and entropy) within the disk for ~ 10 turns. Below this density the enhanced alpha viscosity no longer can transmit torque, and the SGR phase terminates. A quiescent, and therefore cooling disk of matter, roughly 100 g cm^{-2} thick, $\sim 10^{30}$ g in total mass, extending out to several AU, circulating around a neutron star, is then the starting point for planetesimal and then planet formation.

THE FORMATION OF PLANETESIMALS

The only difference between the protoplanetary disk of the sun and that of the depleted SGR is that the former is formed by accretion of a solar mass from the outside and the SGR disk is formed from the inside by the same α viscosity but acting within a smaller mass, $\sim 0.1 - 0.01 M_\odot$, initially captured by the neutron star from its companion at formation. Thus the disk around neutron star extends only to $3 - 10$ AU. Thus the inner disks of the solar and neutron star should be similar, but with likely enrichment in condensible solids of the captured disk. Thus the evolution time to solid planetesimal sizes should be similar. We next summarize a simplified theory of planet formation from reviews by Pollack [6], by Lissauer [7] and by Woolfson [8].

Both geophysical evidence and theoretical modeling lead to times for the formation of the earth of a few $\times 10^7$ years. We consider next the sequence of growth by accretion (or sticking) in the disk of bodies whose geometric cross section (σ_{geo}) is less than their gravitational scattering cross section (σ_{grav}), or bolloids. We reserve the word planetesimals to describe bolloids large enough such that $\sigma_{geo} > \sigma_{grav}$.

• The Growth of Molecules. As the now stable accretion disk matter cools, molecules of metal oxides and silicates bind first, leading to a high temperature gas of these condensible solids. Further cooling and the first molecules collide and initiate crystal or grain growth. One can estimate a characteristic time for this process from the number density n, collision cross section σ and RMS velocity v_{RMS}, $\tau_{collision} = 1/(n\sigma v_{RMS})$. We can further divide the cross section into a geometric part (σ_{geo}) and a sticking probability s, where $s \sim 0.01$ for both crystal growth as well as for very much larger bodies like rocks and boulders, provided in both cases, the velocity is not so great as to destroy the molecule, grain, or bolloid. We further note that $n \propto 1/H$ where H is the height of the disk, and $H = R(v_{RMS}/v_K)$ where R is the orbit radius with Keplerian velocity v_K. If we consider a molecular weight of $A \sim 100$ for the condensibles and $\sigma_{geo} = \pi r^2_{molecule}$ where $r_{molecule} \sim 2 \times 10^{-8}$ cm. Then the density will be 2.5 g cm^{-3}, like rock, and the geometric collision time leads to $\tau_{molecularcollision} \sim 5 \times 10^{-3}(R/R_{AU})^{3/2}$ seconds, which becomes ~ 0.5 s with a small sticking probability of 1%.

• The Growth of Bolloids and the Formation of Planetesimals. We now extend this growth rate to larger bodies noting that the geometric cross section scales from molecular sizes to bolloid sizes. As the particles grow in size, they decrease in number for a fixed total mass in orbit so that $\tau_{growth} \propto m_{particle}/r^2 \propto r$. This implies that all the time of accretion is spent at the largest bolloid size. This scaling breaks down when a bolloid reaches a critical mass (i.e., planetesimal) such that the gravitational potential at its surface exceeds the RMS kinetic energy of its "thermal" distribution. Note that v_{RMS} is both heated by the Keplerian velocity shear and cooled by disintegrating collisions. A natural velocity limit is when the dynamic pressure of impact of bolloids is within the strength of the bolloids or simply that of rock. (For the outer planets where ice forms the principle solid, the critical velocity will be considerably less.) This dynamic pressure, $P_{dynamic}$ is ~ 100 atmospheres, so $m_{planetesimal} \propto P^{3/2}_{dynamic} \sim 10^{22}$ g at a radius of $r = 10^7$ cm. A statistical wide range of $m_{planetesimal}$ is likely. Thus at a critical mass of a planetesimal of $m_p \sim 10^{22}$ g, $r_p \sim 10^7$ cm, and velocity $v_p \sim \sqrt{Gm_p/r_p} \sim 10^4$ cm/s, the growth time is $\tau_{growth} = \tau_{moleculargrowth}(r_{planetesimal}/r_{molecule}) = 1.5 \times 10^7$ y at an orbit of an AU and ~ 50 million years at 3 AU. This thus spans the desired turn on time of the GRBs.

• The Formation of a Planetoid. Once the planetesimals reach this critical mass/size, run-away accretion takes place due to the gravitationally-enhanced collision cross section. The importance of gravitational scattering in the evolution of the planetesimal mass distribution has been calculated and emphasized by many authors, particularly by analogy to plasma physics by Safronov [9] and later by Goldreich, by Tremaine and by Ward [10], [11], and numerically confirmed by Aarseth, Lin, and Palmer [12], [13]. The run-away accretion is so fast that nearly all the evolution time is spent reaching the critical size, $m_{planetesimal}$ and little time afterwards. Part way through the run-away accretion process to the planet size, an intermediate condition of a "proto planet" of perhaps $m_{protoplanet} \sim 10^4 \times m_{planetesimal}$ will form. The strong large angle scatterings between proto planet and planetesimals lead to heating rather than cooling of v_{RMS}. So a fraction of the planetesimals will diffuse in orbit exactly the same as we even now observe comets scattered by Jupiter and Saturn into the inner solar system. This is the initiation of the GRB phase.

THE FORMATION OF THE GRB

Once scattered inside a radius of $\sim 10^{11}$ cm from the neutron star in an elliptical orbit, the planetesimal will break-up due to tidal forces and the limited strength of rock. The friction between fragments at periastron will ensure evolution to a circular orbit and further evolution by friction describes an accretion disk of rock fragments around the neutron star. The pressure within the disk becomes $P = (\Sigma H)(M_{NS}G/R^2)(H/R)$, which should be supported by degeneracy pressure, $P_{degen} \gtrsim 10^{13}$ dynes cm^{-2} at a radius of $\sim 3 \times 10^8$ cm. This degenerate, fluid disk evolves in density and energy density reaching the Alfven radius where $P_{degen} = B^2_{dipole}/8\pi$ or at $R_{Alven} \sim 10^7$ cm. This is then a thin conducting disk rotating in a strong dipole field, or a classical unipolar generator. The electrical break-down of this generator is ensured because of the high potential, between dipole lines of force threading both the neutron star and the inner most and outer radii of the disk. This voltage is $V_{unipolar} = \int B \times (v_{keplerian}/c)dR = 5 \times 10^{19} B_{12} R_{NS}((R_1/R_{NS})^{-5/2} - (R_2/R_{NS})^{-5/2})$ volts or 1.5×10^{17} volts at R_{Alfven}. The strong torque due to the current $I_{unipolar}$ crossing the field lines in the disk allows rapid accretion onto the neutron star, while the current outside of the disk flows parallel to field lines and we assume that it may excite a disruption instability. As in the classical tokamak disruption (possibly due to lower hybrid waves), all the current is carried by relativistic runaway electrons, which will radiate synchrotron emissions in equilibrium with their acceleration. Then the GRB luminosity is the electrical power, or $L_{GRB} = I_{unipolar} \times V_{unipolar} = 10^{41}$ ergs/s and thus $I_{unipolar} = 2 \times 10^{14}$ amperes at R_{NS}. Balancing the synchrotron cooling with acceleration, runaway electrons can achieve maximum *gamma* from $I_{unipolar} \times V_{unipolar} = (4/3)(I_{unipolar} R_{NS}/e)\gamma^2 (B^2_{NS}/8\pi)\sigma_{Compton}$. Then $\gamma^2 B_{12} = 2.3 \times 10^3$ and the photon emission, $\gamma^2 h\nu_{cyclotron}$ would be at ~ 30 MeV. But these high energy photons will immediately cascade through pair creation in the magnetic field creating a pair plasma further limiting the particle γ. The emission from the creation and annihilation of this pair plasma is the GRB.

When a GRB with the emission of $\sim 10^{41-42}$ ergs occurs at the center of the planetesimal distribution, the gamma ray flux penetrates the surface of all bolloids as well as the planetesimals a distance determined by the gamma ray mean free path. The specific heat of the matter corresponding to this depth as well the flux determines the rate of heating and blow off velocity. Provided the surface is heated to the vaporization temperature, then for a heat flux of $\sim 10^{14-15}$ ergs $cm^{-2}s^{-1}$, a mean gamma ray energy of $\sim 1/4$ Mev, and delivered in bursts over a period of seconds, a mass of $\sim 10^{3-4}$ g cm^{-2} will be ablated at a velocity of $\sim 3 \times 10^5$ to 10^6 cm/s. As a consequence a planetesimal will recoil with a positive, radial velocity impulse of $\Delta v_{RMS} \sim 0.01 - 0.03 \times v_{RMS}$. The progressive heating of v_{RMS} by a sequence of ~ 100 bursts will prevent further accretion of planetesimals until cooling has again taken place. This cooling should take roughly 100 orbits or 100 years and so determines the frequency of GRBs. This also determines the depletion time or turn-off time of the GRB phase, namely 10^6 planetesimals in 10^8 y requiring 10^{28} g or 1% of the orbiting mass after the SGR phase. The x-ray after glow is created from the x-ray fluorescence of the GRB flux as it traverses the ablated matter.

It will be ironic that the delay time, the size of bursts, and the frequency, or equivalently the turn-off time will depend upon something as rudimentary, prosaic, and mundane as the strength of rock.

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