Model for the 5 March 1979 Gamma-Ray Transient

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A model is proposed for the 5 March 1979 γ-ray transient. A small lump of strange matter, previously ejected from a supernova explosion, struck a slowly rotating strange star. This resulted in a high-intensity flash of radiation from a hot spot produced by the impact. The high-intensity radiation blew open a crater in the crust; the energy released as this crater refilled was responsible for the longer-duration, lower-intensity phase. The 8-s modulation is due to the rotation of the star. A plausible scenario for the production of this event is discussed.

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A remarkable burst of γ rays was observed by the interplanetary γ-ray sensor network on 5 March 1979.[1-3] The burst was recorded by instruments on nine spacecraft, and there is no doubt concerning its unusual phenomenology. Specifically, as reported by Refs. 1–5, the maximum intensity during the burst exceeded by more than an order of magnitude that of any other γ-ray burst, with a peak flux of $\sim 10^{-3}$ erg/cm^2 s; the rise time was $\lesssim 250$ μs, more than a hundred times faster than any previously measured burst; the burst had a brief (~ 0.15 s) "high-intensity phase" which is of shorter duration than most γ-ray bursts with an energy fluence of $\sim 2\times 10^{-4}$ erg/cm^2; the high-intensity phase was followed by a "low-intensity phase" which was observed for over three minutes, and in which the average flux of $\sim 10^{-5}$ erg/cm$^2\cdot$s decayed exponentially with a characteristic time of ~ 50 s; the low-intensity phase was clearly modulated with a period of 8 s (altogether 22 periods can be seen in the data), and the first maximum of the modulation occurred 4 s after the high-intensity phase; and the spectrum was different from that of a typical γ-ray burst: The low-energy part of the spectrum ($\lesssim 300$ keV) can be fitted by an exponential with a characteristic "temperature" of ~ 30 keV, while the high-intensity phase has a harder spectrum above 300 keV with a broad feature at 420 keV which is attributed to a red-shifted e^+e^- annihilation line.

An astonishing optical identification was also reported[6]: a young supernova remnant, N49, in the large Magellanic Cloud with the clear implication that the event occurred at a distance of ~ 55 kpc. The supernova remnant lies within the timing error box, which is ~ 1 ft$\times$2 ft in size, and the probability of a coincidence appears to be small.

Much less intense bursts were seen from the same region of the sky on 6 March, 4 April, and 29 April 1979.[1]

The discoverers understood the theoretical difficulties these data present. If the distance is believed, then the energy released during the initial flash is $\sim 7\times 10^{43}$ ergs with a peak luminosity $\sim 3\times 10^{44}$ erg/s, six orders of magnitude in excess of the Eddington limit for a solar-mass object. Models involving an accretion event face an additional difficulty in that the rise time is short compared to the time needed to dump $\sim 10^{25}$ g of material onto a neutron star. No model in the literature accounts for the origin and rapid release of the very large amount of energy, the very high efficiency of the radiation mechanism, and the four very different time scales: the rise time, the durations of the high- and low-intensity phases, and the period of modulation. The theoretical situation has been reviewed by Liang.[7]

We propose the following model for the 5 March 1979 event. A lump of "strange matter" with mass $\sim 10^{-8} M_{\odot}$ and radius ~ 23 m struck a "strange star." Strange matter is bulk quark matter consisting of roughly equal numbers of up, down, and strange quarks is *conjectured* to be the true ground state of the hadrons.[8] Strange matter is stable at zero pressure where it has a density of $\sim 4\times 10^{14}$ g/cm^3. Under this hypothesis, lumps of strange matter could be found with radii ranging from a few fermis to neutron star sizes. In fact, neutron stars would almost certainly be made of strange matter, not neutrons, and we call these stars "strange stars."[8-10] Our strange-matter projectile was so compact that the duration of the impact was comfortably less than 250 μs. The impact heated and exposed a bare quark-matter surface which was capable of radiating at rates greatly exceeding the Eddington limit. The observed high-intensity phase was due to the radiation of heat produced at the site of the impact. The high-intensity radiation opened a crater in the thin crust of normal matter that the strange star supports. After the high-intensity phase the hole filled and the heat generated was responsible for the lower-intensity phase. The 8-s modulation is attributed to the rotation of the star.

I. *Strange matter and strange stars.*—Strange matter is stable quark matter.[8] It consists of roughly equal numbers of up, down, and strange quarks plus a smaller number of electrons (to guarantee overall charge neutrality). A detailed calculation[11] showed, within the uncertainties inherent in any strong-interaction calculation, that the existence of strange matter is plausible. Strange matter may come in lumps with baryon number ranging from 100 up to 2.5×10^{57}. The lower limit arises from shell effects.[11] The upper limit corresponds to a mass $\sim 2M_\odot$ and is determined by gravitational collapse. Objects in this mass range resemble neutron stars. Furthermore, in this picture it is reasonable to assume that there are no "neutron stars," only strange stars.[8–10] A strange star may have an exposed quark surface which, since it is held together by the strong interaction, is not subject to the Eddington limit. However, since the "plasma frequency" in the quark matter is ~ 20 MeV, this surface is not effective at emitting photons of energy much lower than 20 MeV.[10]

A strange star may support a thin crust of material which is the same as the "outer crust" of neutron stars.[10] This crust is made of ions arranged in a solid lattice together with degenerate electrons.[12] The precise nuclear configurations are history dependent, since they depend on whether or not baryon-number–changing nuclear reactions have occurred.[13] In any event, the nuclei near the base of the crust have a high neutron-to-proton ratio. The crust is supported electrostatically with a gap preventing reactions between the nuclei and the strange matter. The base of the crust must be at a pressure below the pressure at which "neutron drip"[12] occurs, because free neutrons would react with the strange matter; this requirement limits the mass of the crust on a $1.4M_\odot$ strange star to no more than 5×10^{28} g.

II. *The model.*—Imagine that a $10^{-8}M_\odot$ lump of strange matter (radius ~ 23 m) falls into a $1.4M_\odot$ strange star. The star is presumed to have a crust of mass 5×10^{28} g and thickness 300 m. The star rotates with a period of ~ 8 s.

In what follows we make assumptions about the conversion of energy into detected radiation. If our assumptions prove overly optimistic, the mass of the projectile can be increased accordingly.

The projectile originates far from the star so that its total energy (kinetic plus potential) is near zero, and as it approaches the $1.4M_\odot$ strange star (radius ~ 11 km) it attains a velocity of $\sim 0.6c$. The mean density of the lump (4×10^{14} g/cm^3) is not much less than the mean density of the star (5×10^{14} g/cm^3), with the important consequence that the lump suffers only a mild distortion due to the tidal field of the star. This is one advantage of the model; the accreting matter arrives in one piece without the tidal disruption that attends the accretion of normal matter onto a neutron star and the rise time for the event can be less than a millisecond. The projectile bores a hole through the crust of the star before it impacts on the quark matter. The maximum density of the crust is $\sim 4\times10^{11}$ g/cm^3 which is much less than the density of the incoming lump. The lump easily passes through the crust and leaves a pencil-like hole behind.

The projectile has a kinetic energy of $\sim 3\times10^{45}$ ergs. The speed of impact is roughly the speed of sound in the quark matter ($c/\sqrt{3}$) so that in fluid dynamical terms this event is not dramatic. The decelerating quark matter is brought to rest locally by microscopic interactions among the quarks. This leads to local heating of the quark matter, and some of the kinetic energy of impact goes into local heat. The balance of the energy goes into the excitation of normal modes of the star.

The incoming lump is a Fermi gas just like the star; however, its Fermi distribution is boosted up to $\sim 0.6c$. At this velocity, roughly half of the quarks of the lump have momenta above the Fermi momentum of the star. After impact, local interactions between the quarks will isotropize the distribution of momenta and bring all momenta within the Fermi sphere of the quarks in the frame of the star. This stopping will generate as much as $\sim 1.5\times10^{45}$ ergs in heat, heating a region the size of the lump up to a temperature of order of a few tens of megaelectronvolts.

A. The high-luminosity phase: At this stage, the local hot spot begins to radiate its heat. The local flux is determined by the high local temperature; not only photons, electrons, positrons, and neutrinos are emitted, but also neutrons and protons.[14] This hot mixture is initially collimated by the hole punched through the crust, but so much energy is forced through the hole that a much larger hole is opened up and the radiation pattern will not be collimated.

The hot spot, with a radius greater than 23 m, and a temperature above 20 MeV, can radiate 1.5×10^{45} ergs in less than one tenth of a millisecond, comfortably below the rise time and duration of the event. Roughly half of this energy is radiated in neutrinos which pass freely through the crust. Most of the remaining energy goes into widening the hole and forming the crater. If we assume that 10% of this energy ultimately appears in γ-ray photons, we can account for the energy observed in the high-intensity phase. The emitted radiation forms a cloud which expands at the speed of light and adiabatically cools until all thermalizing reaction rates fall below the expansion rate. If we consider only thermal e^+e^- pairs and photons, this happens at ~ 20 keV when Compton scattering rates become small (the photon-photon scattering rates become small sooner, at ~ 100 keV). The cloud freezes at this temperature which is characteristic of the observed soft part of the spectrum.

At a temperature of 20 keV the cloud has a radius ~ 2300 km which implies a difference in arrival times of ~ 8 ms between the first and last photons of the initial peak. This underestimates the duration of the initial phase by a factor of 15. Electrons from the crust might be entrained in the cloud, increasing the number of scatterers and therefore the Compton scattering rate. This will imply a longer time to cool and a lower temperature. More complicated physical processes will also lengthen the burst; for example, emitted protons and neutrons will continuously fall back onto the hot spot and prolong the reactions.

The e^+e^- pairs created close to the surface may be trapped by the strong magnetic field and be responsible for the hard tail above 300 keV due to synchrotron cooling and pair annihilation as in Ref. 5 and inverse Comptonization as in the work of Liang.[15]

B. The low-luminosity phase: The intense radiation from the hot spot during the high-luminosity phase will blow open a large crater in the crust of the star. The crust is bound to the star gravitationally and hence is subject to the Eddington limit. The size of the hole is difficult to calculate, but most likely all of the crust within the line of sight of the radiating region will be dislodged. Geometrically, this corresponds to a cap of radius ~ 2.5 km. If most of the heat generated at the impact goes into lifting of the crust, then this cap can reach an average height of ~ 200 m. Thus, we expect a large crater to form along with the initial burst.

The material around the crater will fall and flow in, filling the hole and generating heat. The observed 1.4×10^{44} ergs can be accounted for if we assume that the crater has a radius of ~ 1 km and a depth equal to the crust thickness, and that 16% of the gravitational energy, released as the hole fills, appears as detectable radiation. We have not been able to estimate the duration of this phase, but it is possible that it could last a few minutes.

III. *The astronomical setting.*—The identification of the 5 March 1979 event with the supernova remnant N49 in the large Magellanic Cloud is the evidence that extraordinary luminosities are involved. The age of this remnant is $\sim 16\,000$ years (see Dopita and Mathewson[16] for a discussion of the age), which implies a young age for the strange star. However, the 8-s periodicity, which we attribute to rotation, is clearly indicative of a much older object such as a defunct pulsar.[17]

This discrepancy suggests the following astronomical scenario for our model. The system consists of a pair of strange stars, one of which was born $\gtrsim 10^7$ years ago, the other $\sim 16\,000$ years ago. Such a system is not unusual since of ~ 400 known pulsars, 6 are in binary systems with either white-dwarf or strange-star companions[18] and its rarity is consistent with the uniqueness of the 5 March 1979 event.

The strange-matter projectile was produced during the supernova explosion 16 000 years ago. Asymmetries resulting from angular momentum might have caused this to happen just after core bounce. If as much as $0.1 M_\odot$ of material were ejected in this way, as many as 10^7 lumps of the kind invoked in Sec. II could be produced. Some of this material might be ejected completely from the system, but a nontrivial amount would remain bound to the star.

The objects that remain bound to the star form a rather crowded little "solar system" in which future evolution is dominated by the few large-mass objects ("Jupiters") which gravitationally scatter much smaller-mass objects ("comets"). As the smaller-mass objects are scattered into higher-energy orbits, some will evolve into orbits which cross the inner Lagrange point of the potential of the binary system. An object of this kind probably has a stochastic orbit and eventually it will strike one of the stars.

The degree of modulation of the low-intensity phase and its phasing relative to the initial peak help us reconstruct the orientation of the older star relative to the observer when it was struck. In a star-based spherical coordinate system with the rotation pole designated "north," let 0° longitude run through the impact site. The phasing implies that the vector to the earth, at the time of impact, was close to longitude 180°. Since the impact was seen and the secondary phase was modulated by roughly half an order of magnitude, the angular separation between the impact site and the initial vector to the earth lies between $\sim 70°$ and 90°.

IV. *Discussion.*—We have described a model for the 5 March 1979 γ-ray transient which plausibly accounts for the phenomenon. A small projectile made of strange matter struck a strange star. The high-density of strange matter ensured that the projectile was not tidally disrupted during infall, therefore the short rise time of the event. The brief intense flash of γ rays was the radiation from a small hot spot produced by the impact. The longer, lower-luminosity phase resulted from the healing of the crater formed in the crust.

The system in which this event occurred is probably a binary system containing two strange stars. One star is $\gtrsim 10^7$ years old and rotates once every 8 s, and is the star which was struck by the projectile. The other star is $\sim 16\,000$ years old, was produced in the recent supernova, and is responsible for the production of the projectile.

If there are, as we suggested earlier, of order 10^7 lumps of strange matter in this system, further intense γ-ray events may be observed. We can make a number of predictions about such events based on the model we have described. Clearly, the total energy of any future event will depend on the mass of the projectile, which we do not know. However, we may predict that the fluence of the low-luminosity phase will not exceed the fluence recorded on 5 March 1979, by more than an order of magnitude. This is because the maximum-size crater possible is at most three times as wide as the crater we considered, and the energy efficiency cannot be much above what we assumed. The modulation of the low-intensity phase will depend on the orientation of the impact and on which star is struck. If the older star is struck the period of modulation will again be 8 s. If the younger star is struck the period of modulation may be too short to resolve with the instruments available.

Events such as these may occur in other systems in which case they may qualitatively resemble the 5 March 1979 γ-ray burst. In our model each of these events would be associated with an intense neutrino burst. However, present neutrino detectors would not have been sensitive to the 5 March 1979 event. If the system were a factor of 3 closer or the projectile ten times as massive, detectors such as the proposed large-volume detector at the Gran Sasso Laboratory[19] could detect the associated neutrino burst in coincidence with the γ-ray burst.

This model illustrates some of the unusual properties of strange matter which may be important in high-energy astrophysics.

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