ONE DIMENSIONAL HYDRODYNAMICS OF ASTEROID-NEUTRON STAR COLLISIONS

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It has been suggested by several authors (e.g., Harwit and Salpeter, 1973) that the observed cosmic gamma-ray bursts might be produced by the collision of comet or asteroid-sized bodies with a compact object. Colgate and Petschek (1980) have discussed the tidal breakup of a solid body approaching a neutron star in central impact, with particular application to the cosmic gamma-ray burst of March 5, 1979. In this work we present the results of simplified one-dimensional hydrodynamic-radiation diffusion calculations of such an occurence.

The source of the projectile in such a collision is somewhat problematical. Events accompanying the formation of a neutron star are believed to be quite violent. It is not clear whether any bound debris orbiting the pre-neutron star in analogy to the cometary or asteroidal matter of our own solar system would survive a supernova explosion as a member of the neutron star system, or whether the disruption of any possible planetary-size objects present could serve to populate the system with such debris. In any event it requires a very special perturbation from bound orbit to produce the kind of direct collision required.

Newman and Cox (1980) have considered the probability of collisions with cosmic debris and estimate the mean time between collisons per neutron star as

$$t \simeq 2.9 \times 10^5 \text{ yr.} \quad \frac{M_{ast}/10^{17}\text{g}}{M/M_{\odot}} \quad \frac{u_{\infty}/20 \text{ km s}^{-1}}{\left(\frac{R_{ns}}{10 \text{ km}}\right)^2 (u_{esc}/10^{10} \text{cm s}^{-1})^2}$$

where a typical "asteroid" has mass M_{ast}, an amount of matter M per pc^3 is in the form of such objects, the mean velocity of approach far from the neutron star is u_{∞}, the velocity at the neutron star radius R_{ns} is u_{esc}, and the time between collisions scales in

Space Science Reviews **27** (1980) 591–594. 0038–6308/80/0274–591 $00.60.

the manner indicated with the uncertain quantities involved. E.M. Jones of LASL points out that studies of galactic dynamics indicate that the average density of all matter in the solar neighborhood is about 0.15 $M_\odot$ pc^{-3}, with about a third of that in the form of stars and the bulk of the remainder in the form of hydrogen and helium, thus severely limiting the quantity M above (to perhaps $M \lesssim 0.003$ $M_\odot$).

Pulsar observations and standard stellar evolution theory indicate that there may be $N_{ns} \lesssim 0.03$ neutron star per pc^3 in the disk of our Galaxy (Lamb et al., 1973). If we observe N events each year, we must pick up all collisions within a distance

$$d = (3Nt/4\pi N_{ns})^{1/3}$$
$$= 132 \text{ pc } N^{1/3}((t/2.9 \times 10^5 \text{yr})/(N_{ns}/0.03 \text{ pc}^{-3}))^{1/3}.$$

Depending on the absolute intensity of the radiation resulting from a collision of the kind considered here (and therefore upon the distance at which it can be detected) it seems possible that most of the more intense cosmic gamma ray bursts observed each year may be due to such collisions.

Although the problem of treating an asteroid-neutron star collision in radiation-hydrodynamic detail is properly a two- or even three-dimensional one, a spherically symmetrical approach can be quite useful. The initially irregular or roughly spherical body is highly distorted as it is elongated by the strong tidal effects near the compact object, and impacts as a long narrow column. Howard et al. (1980) found in their two-dimensional calculations with no magnetic fields and a perfectly rigid neutron star surface that the hot shocked matter spreads rapidly over the neutron star surface and cools, building up an optically thick cloud which obscures the hot spot of interest and degrades the emergent radiation. Colgate and Petschek (1980) point out that in the strong magnetic fields ($\sim 10^{12}$ gauss) to be expected at the neutron star surface the hot matter will be confined to flux tubes that intersect the accretion column. Newman and Cox (1980) found that the asteroid-neutron star interface penetrates the neutron star surface to significant depths (in terms of density of the surrounding matter) before it is forced above the original position of the surface by the energy released in the collision, a behavior not allowed by the boundary condition of Howard et al. These latter effects mitigate the importance of edge effects, and suggest that the one-dimensional calculations reported here might represent well conditions in the center of the impacting column.

https://doi.org/10.1017/S0252921100082105 Published online by Cambridge University Press

The neutron star was chosen to have mass 1 $M_\odot$ and radius 10 km, with initial luminosity 1 $L_\odot$ and effective temperature 1.5×10^6 K. The outer $\sim 10^{22}$ g of the hydrogen atmosphere (a thickness of a few meters) was represented explicitly in the calculation, occupying the inner 25 zones of our Lagrangian mesh. The outer 25 zones represented the asteroid, idealized as a shell of thickness Δr and density ρ which approaches the neutron star at velocity u. The calculation began in the instant of impact. The maximum temperature at the interface and the effective temperature at the asteroid surface proved to be insensitive to the composition of the asteroid layer, and iron asteroids were chosen as the standard. Temperatures resulting from the collision were produced by the conversion of kinetic energy to thermal energy, and thus depended sensitively on the choice of impact velocity. Velocities near the escape velocity $u = -1.6 \times 10^{10}$ cm s^{-1} were required to produce temperatures characteristic of cosmic gamma ray bursts. $u = -1.0 \times 10^{10}$ cm s^{-1} was adopted as the standard.

The intensity and character of the gamma-ray burst resulting from such a collision is a compromise between compressing the interface region by a sufficient overburden of infalling material to heat it to the desired extent, and restricting the overburden so that the radiation can get out without being excessively degraded by absorption and reemision in cool outer layers. Satisfactory candidates for cosmic gamma ray bursts (effective temperatures of several times 10^8 K, luminosities of a few times 10^{43} ergs s^{-1} (scaled by the ratio of the area of the hot spot to the area of the neutron star surface)) were found for surface densities of asteroid material $\sigma = \rho\Delta r$ of 10 to 100 g cm^{-2}. The extreme case $\rho = 10$ g cm^{-3}, $\Delta r = 1$ cm (corresponding to asteroid mass 1.3×10^{14} g distributed uniformly over the entire neutron star surface) yielded a peak luminosity of 1.8×10^{44} ergs s^{-1}, sufficient to have placed the March 5th cosmic gamma ray burst in the Large Magellanic Cloud as suggested by the direction to its position error box. (Note that even though the luminosity exceeds the Eddington limit for a brief time the resulting deceleration is not sufficient to expel the incoming matter in the time available.) Although the effective temperatures and luminosities of the events studied were sufficient to make them candidates for cosmic gamma ray burst sources, the time scales of the collisions ($\sim 10^{-8}$ s) were much shorter than those of observed bursts ($\gtrsim 10^{-1}$ s). The distended columns of the sort found by Colgate and Petschek and Howard et al. could sustain the burst for the times required. The time scale of the main burst is determined by the tidal disruption patterns and the spread of arrival times of matter at the neutron star surface. A black body spectrum need not result from the superposition of regions of different temperature with different effective surface areas as the sustained collision evolves. An event like the March 5, 1979 gamma ray burst, with its observed double 4 sec. periodicity following the main pulse, is understood in terms of remnant debris following the magnetic field lines to impact the magnetic polar caps for a period of minutes following the initial deposition of the bulk of the asteroidal matter, maintaining the two opposed polar hot spots which come alternately into our field of view once each half-revolution.

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DISCUSSION

HUGHES: Would you expect to notice asteroids hitting ordinary stars which will happen at an enormously greater rate?

NEWMAN: No. I don't think so. The gravitational potential well of the compact object is enormously larger than for a star like our sun. It requires a compact object to get a gamma ray source.

HUGHES: How often would you expect these regular stars to have collisions?

NEWMAN: All the time.

COLGATE: You notice that you have to put most or half of the matter in the galaxy into asteroids in order to get an acceptable rate of gamma bursts.

JOSS: Won't the tidal effects tend to give low densities and a spread in time of impact much less than 0.1 second?

NEWMAN: The tidal disruption is an essential part of the problem and one that Colgate and Petschek have been working on very hard. It is a difficult 2D problem that Weaver at Los Alamos and Howard at Livermore have been studying also. The asteroid will be heavily stretched like a needle or funnel. Our 1D calculations may not be relevant, but the central regions of the actual collision may have some features of our collisions.

PETSCHEK: I am amused by your model in which the asteroid goes splat first and then hits afterwards.

JONES: Have you considered how often these things ought to impact the lunar maria?

NEWMAN: The lunar bombardment is due mostly to matter found in the solar system.

COLGATE: Most of the neutron stars have high velocities in the galaxy. Either the gamma bursts come from the small number of low velocity neutron stars or the collision rate needs to be redone for the higher velocity.