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We wish to point out a possible association between cosmic gamma-ray bursts(1) and transient X-ray sources. We find that the gamma-ray burst of April 21, 1971 could have signalled the birth of the transient X-ray source 2U 1543-47.

Five transient X-ray sources have been reported with a frequency of $\sim 1\ \text{year}^{-1}$: Cen X-2 (Ref. 2), Cen X-4 (Ref. 3), 2U 1735-28 (Ref. 4), 2U 1543-47 (Ref. 5) and Cep X-4 (Ref. 6). As sky coverage is not complete for transient X-ray sources, it is conceivable that the actual frequency of these objects is comparable to that of γ-ray bursts. We have compared both the starting times and positions of these sources with the dates and available positional information of gamma-ray bursts(7). For a correlation we demand that the position of the gamma-ray burst and X-ray source should coincide, and that the date of the gamma-ray burst should precede the starting time of the transient X-ray source. However, because the lifetime of the X-ray sources is about a few months, an acceptable candidate gamma-ray burst should not precede the start of the X-ray source by more than such a time interval.

We have found a possible association between the April 21, 1971 gamma-ray burst and the transient X-ray source 2U 1543-47 (Ref. 5). This X-ray source appeared some time between March 25, 1971 and August 17, 1971, and its intensity decreased by about an order of magnitude by December, 1971. The position of 2U 1543-47 was $\alpha_1 = 235\overset{\circ}{.}96$ and $\delta_1 = -47\overset{\circ}{.}56$ with an error of about $0\overset{\circ}{.}5$. The gamma-ray burst of April 21, 1971 was observed by 2 satellites of the Vela system, and thus only a circle of positions could be determined. The center of this circle was at $\alpha_2 = 247\overset{\circ}{.}4$ and $\delta_2 = 34°$, and its radius was between $80\overset{\circ}{.}8$ and $85\overset{\circ}{.}2$ (Ref. 7 and I. B. Strong, private communication, 1973). The error in the position of the center of the circle is small in comparison with the error in angular size of the radius. The angular separation between the X-ray source and the center of the position-circle of the gamma-ray burst is $82\overset{\circ}{.}2$, i.e. well within the range of radii of the position circle. Thus, both the temporal and positional data are consistent with an association between the burst of April 21, 1971 and 2U 1543-47.

The γ-burst error circle has a total solid angle which is less than 0.04 of 4π, so that 0.04 is a fair estimate of the probability of a random association between the burst and 2U 1543-47 with regard to the positional coincidence alone. There is, however, one other γ-ray burst (that of June 30, 1971) in the temporal window for which there is no positional information. If we allow some delay between the γ-ray burst and the appearance of the X-ray source, there are bursts on January 2, March 15 and March 18, 1971 which might also be candidates, but there is no positional information for the January 2 burst, and the other two have positions which cannot be reconciled with 2U 1543-47.

We have searched for associations of the other transient X-ray sources with γ-ray bursts, with inconclusive results. No γ-ray bursts the August 22, 1970 burst as seen by detectors on 3 different satellites. This burst consists of 2 peaks separated by about 6 seconds, with considerable fine structure within the first peak. Because the time resolution of the experiment decreases with time after the initial trigger, it cannot determine whether similar fine structure exists in the second peak as well. This double peaked structure seems to be a property of a fraction of the gamma-ray bursts; some bursts are single, but others show three or more peaks on a time scale of 10 to 20 seconds.

The exact rise times of the bursts is not known but rapid fluctuations on time scales less than 1/64 seconds have been observed on several occasions. The decay time of the first peak is about 1 to 2 seconds, and that of the second peak appears to be of the same magnitude. Among the single peaked bursts, however, there are events with shorter decay times as well.

We propose the following sequence of events to account for the gamma-ray bursts. A white dwarf accreting matter (possibly from a binary companion) collapses when its mass exceeds the Chandreshekhar limit. Since this limit is less than the maximum stable mass of a neutron star, the collapse should proceed to a neutron star. This process releases about 10^{53} ergs of gravitational energy.(1) Most of this energy is carried away by neutrinos(8), but a significant part of it can be in heat and in pulsations.

A collapsed hot object is expected to emit blackbody radiation(9) with luminosity L given by

$$L = 4\pi r^2 \sigma T^4 \qquad (1)$$

where, $\sigma = 5.7\times10^{-5}$ erg $(°K)^{-4}cm^{-2}sec^{-1}$, r is the radius, and T is the surface temperature. The observed photon flux density of the bursts (measured in photons $cm^{-2}sec^{-1}keV^{-1}$) is proportional to exp $(-E/E_o)^{(5)}$, where E is photon energy and E_o is a parameter which varies from event to event but is generally in the range from about 100 to 200 keV. A blackbody spectrum with constant temperature is not consistent with such a spectrum. However, a cooling blackbody does provide a very good fit to the observations.(4) The point is that the spectral measurements are made over time intervals of the same order as the duration of the bursts, and the temperature is expected to vary over this interval. The deduced initial temperature of the bursts is about 2×10^9 °K.(4)

Cocke and Cohen(10) have studied the large amplitude pulsations of a degenerate star oscillating between radii of about 10^6 to 3×10^8 cm. The period of these oscillations is about a few seconds. These pulsations can account for the 6 seconds separation between peaks in the burst. The large neutrino luminosity,(8,10) however, will rapidly damp the oscillations. This can explain the transient nature of the bursts, as well as the observation that some bursts do not show multiple peaked structures.

The descent of the unstable white dwarf into the neutron star configuration takes place in a time comparable to the free-fall time. Since the gravitational energy is expected to be released close to the neutron star radius, the rise time, t_r, of the bursts should be of the order of the free-fall time from a radius comparable to the radius of the neutron star,

$$t_r \simeq (\pi/2) r^{3/2} (2GM)^{-1/2} \qquad (2)$$

Here G is the gravitational constant and M is the mass of the star. For M = 1 solar mass and $r \simeq 3$ neutron-star radii, t_r is about 5×10^{-4} seconds. This time is much shorter than the presently available observational upper limit on the rise time; future observation of rise times of the order of milliseconds will provide observational support to the present model.

The decay times of the bursts are probably determined by the cooling of the star. The time-integrated gamma-ray flux of the bursts is in the range 10^{-5} to 2×10^{-4} erg cm^{-2}(Ref. 2). With a duration of 2 seconds and $T \simeq 10^9$ °K, Equation (1) yields:

$$0.8\times10^{18} r \leqslant d \leqslant 3\times10^{18} r, \qquad (3)$$

where d is the distance to the source and r its radius, both in centimeters. With r in the range 10^6 to 3×10^8cm, d is between 0.2 to 300 Mpc.

Thus, for our model to be valid, the bursts should be extragalactic, because the lower limit on d is greater than any galactic dimension. The upper limit on d is much greater than the distance to the Virgo cluster (~ 10 Mpc, Ref. 11). Most of the galaxies within a distance of about 10 Mpc from our own are in the Virgo cluster ($\ell^{\Pi} = 284°$, $b^{\Pi} = 74°$), but among the seven bursts for which arrival directions are known,(12) none come from this cluster. This means that the sources of the majority of the bursts are probably farther than about 10 Mpc. If the minimum distance is about 25 Mpc, say, then the minimum size is about 10^8cm and the minimum gamma-ray luminosity is $\sim 7\times10^{48}$ erg sec^{-1}. In our model, the maximum size is about 3×10^{8} cm: hence the maximum luminosity is $\sim 7\times10^{49}$ erg sec^{-1}. Because the total energy released during the collapse is $\sim 10^{53}$ ergs, the gamma-ray efficiency is about 10^{-4} to 10^{-3}. Also, for r in the range 10^{8} to 3×10^{8} cm, eq.(3) yields 25 Mpc $\leqslant$ d $\leqslant$ 300 Mpc. With a density of 0.03 galaxies per Mpc^{-3} (ref. 11), the observed rate of ~6 gamma-ray bursts per year implies that the rate per galaxy is greater than about 1 event per 5×10^{5} years. On the other hand, because no bursts were seen from the ~2500 galaxies in the Virgo cluster(11), the rate of gamma-ray bursts per galaxy is less than about 1 event per 400 years.

The observed temporal structure of the gamma-ray bursts could be due to oscillations. As discussed above, the second peak at about 6 seconds could be due to a rebound of the neutron star. The fine structure within the first peak could be caused by oscillations of the rebounding star. Because the radius of the star during rebound is intermediate between the radii of a neutron star and a white dwarf, its oscillation period could also be intermediate between the oscillation periods of such objects. The period of a white dwarf is of the order of a few seconds(13), and the period of a neutron star is about 10^{-3} seconds(14). These periods bracket the time constants of the fine structure which are of the order of a few tenths of seconds.

The principal observational tests of our model are:

1. Spectral measurements over narrow time intervals (~0.1 seconds) which would confirm the blackbody nature of the emission.

2. Observation of the rapid rise time of the bursts ($\sim 10^{-4}$ seconds). However, because the radius of the object is expected to increase as a result of the rebound of the star, there could be an additional slower increase of the intensity after the initial rapid rise.

3. Detection of a neutrino burst in coincidence with the gamma-ray burst.

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During the formation of neutron stars, large amounts of gravitational binding energy ($\sim 10^{53}$ ergs) are released(1), and a small fraction of this energy could go into prompt high-energy photon emissions. We propose that such emissions could account for the recently observed gamma-ray bursts of cosmic origin(2).

Because the prompt nature of the bursts indicates little absorption of gamma rays, we expect that these neutron stars are not surrounded by large amounts of matter. This might explain why no optical supernovae were observed in coincidence with the gamma-ray bursts. The neutron stars could be formed from collapsing white dwarfs(3), the collapse being caused by accretion which raises the mass above the Chandrashekhar limit. The rise time of the bursts should be of the order of the free-fall time of the star from a radius comparable to the radius of the neutron star ($\sim 10^{-4}$ seconds). The gravitational energy released during the collapse heats the star and causes the emission of neutrinos. The surface of the star radiates as a blackbody; we have shown(4) that blackbody radiation of variable temperature can explain the observed spectra of the bursts(5). The temperature variation is due to cooling: an initial temperature of about 2×10^{9} °K decreases by a factor of 2 to 3 during the observed decay of the bursts of about

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1 to 2 seconds. Time-integrated blackbody emission(4) can then account for the observed spectrum in the gamma-ray region. When the temperature is further decreased, blackbody emission can also account for the x-ray observations(6).

The decay of the bursts is due to cooling or other processes which dissipate the initial thermal energy. The double or multiple-peaked structures of some of the bursts could be caused by rebounds(7) of the neutron star. Other observed temporal fine structure could be due to oscillations of the rebounding star.

Considerations of blackbody emission and the possible size of the emitting region imply that the sources of the gamma-ray bursts should be extragalactic at distances from several tenths of megaparsecs to about 300 Mpc. The comparison of arrival directions with the distribution of nearby galaxies limits this range to distances greater than a few tens of megaparsecs. The total gamma-ray energy of the bursts is then 10^{49} to 10^{50} ergs and the frequency of the bursts is greater than about 1 event per 500 years per galaxy.

About twenty short bursts of photons in the energy range from about 100 keV to 1 MeV have been observed over a 3-year period by the Vela satellite system(2). Some of these bursts have also been observed in coincidence by a gamma-ray detector on IMP-6(5) and an X-ray telescope on OSO-7(6). Various time-of-flight techniques and direct directional observations by the OSO-7 detector seem to establish the reality of the bursts and their extra solar-system origin.

Klebesadel et al.(2) have shown as an example the temporal variations of are reported prior to April, 1967, when Cen X-2 was first detected. No γ-ray bursts were detected between July 2, 1967 and July 3, 1969, the latter occurring close to the appearance of Cen X-4 between July 6, 1969 and July 9, 1969, but the positions do not agree. Barring any systematic problem associated with the computation of the γ-ray burst position ring, Cen X-4 is not positionally compatible with the July 3, 1969 burst. No bursts for which there are positional data agree with the appearance of 2U 1735-28 in March, 1971, although there exists a burst on January 2, 1971 which lacks positional information. Similarly, no bursts preceding the discovery of Cep X-4 on June 20, 1972 have positions in agreement with that source, although there are bursts which lack positional data on June 30. 1971, January 17, 1972 and March 12, 1972.

There are at least two explanations for these negative results, assuming that the association with 2U 1543-47 is real. Firstly, not all transient X-ray sources necessarily represent the same phenomenon, and hence not all of them should be preceded by gamma-ray bursts. Secondly, both the X-ray and the burst data are incomplete: positional information is not available for all gamma-ray sources, and, moreover, some bursts may not have been detected by the Vela detectors. However, if the April 21, 1971 gamma-ray burst, being one of the weakest events, was indeed followed by a transient X-ray source, similar associations should exist for other gamma-ray bursts. This could be tested by future X-ray surveys of regions around gamma-ray bursts shortly after their occurrence, but not later than a few months after the date of the burst.

Finally, we mention the time-integrated fluxes. These were about 3×10^{-6} erg cm^{-2} for the burst of April 21, 1971 (I. B. Strong, private communication, 1973), and ~ 0.1 erg cm^{-2} for 2U 1543-47. Thus, if the proposed association is real, the source of these events emits about 3×10^{4} more energy in quasi long-term X-rays than in prompt gamma rays.

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