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X-RAY BURSTS

Observation versus Theory

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Introduction

It is very likely that the common type I X-ray bursts (Hoffman, Marshall and Lewin, 1978) are caused by thermonuclear flashes in the surface layers of accreting neutron stars. Some "bursting" neutron stars are found in low-mass close-binary systems. The mass of the companion stars are typically $\lesssim .7\ M_{\odot}$ and several observed orbital periods range from about one to ten hours. It is very likely that all burst sources are low-mass close-binary systems. (For a comprehensive review, see Lewin and Joss 1981 and 1982).

The most detailed model calculations have been made by Joss, 1978; Taam and Picklum, 1979; Joss and Li, 1980; Taam 1980, 1981a,b; Ayasli and Joss, 1981.

In this article I will compare some observational data with the thermonuclear flash theory as developed to date and I will make some critical remarks which may perhaps remove some confusion and misunderstanding.

Burst Profiles

Comparing the burst profiles from recent model calculations (Ayasli and Joss, 1981) with observations, it seems that the gross features, as observed, are reasonably well explained. However, the double-peaked bursts (Lewin et al, 1976; Hoffman, Cominsky and Lewin, 1980; Grindlay et al, 1980; Hayakawa 1981) are still not explained satisfactorily (see also "Rise and Decay Times" below).

Irregular Burst Intervals

The observed burst intervals, in general, vary from hours to days but occasionally are as short as 5 to 10 min (Lewin et al, 1976; Hayakawa 1981 and references therein). Apparently, occasionally only part of the nuclear fuel flashes and a substantial fraction (about 0.5) remains which can flash about 5-10 min later. This phenomenon has so far not been explained.

Burst intervals can also vary by factors 10 to 10^2 without any appreciable change in the observed persistent X-ray emission. Such variability may be related to variations in the mass accretion rate which may delineate a hydrogen-helium flash from a helium flash. In Taam (1981b) the burst intervals increased from about 12 hours (for the hydrogen-helium flash) to about 400 hours (for the helium flash) for a variation in the accretion rate by only a factor of 3. Variations in the burst intervals from about 1 to 10 hours are, however, difficult to understand. Apparently, during the quiescent burst periods the nuclear fuel burns steadily without flashes. With the exception of an unusually energetic burst from MXB 1728-34 (Hoffman, Cominsky and Lewin, 1980; Basinska et al, 1982) the first burst, after a long "quiescent" burst period, is not exceptionally energetic. It seems plausible to assume that the bursts themselves can change the conditions in the surface layers sufficiently to suppress the short interval bursts.

The thermonuclear flash theory does explain why the burst activity stops when the persistent flux (i.e., the rate of mass transfer) becomes very high (Joss 1978; Ayasli and Joss, 1981). It is well known that MXB 1820-30 (in NGC 6624) only bursts when the persistent flux is relatively low (Grindlay et al, 1976; Clark et al, 1976 and 1977). The same is true for the highly variable source MXB 1659-29 (Lewin, Hoffman and Doty, 1976; Lewin 1978; Lewin et al 1978).

Rise and Decay Times - The Role of Hydrogen

The variety of risetimes and decay times, as observed, seems adequately explained by the theory (see Ayasli and Joss, 1981 and references therein) and it is clear now that even though the helium initiates the flash, hydrogen can play a very important role (Taam and Picklum 1979; Taam 1980; Wallace and Woosley, 1981; Ayasli and Joss, 1981); and can be the dominant factor in the total energy release in a burst.

The risetimes of type I bursts (from a given source) can vary from a fraction of one second to many (about 5-10) seconds. It is incorrect to think that bursts fall in two categories: those with a "fast" rise and those with a "slow" rise. Equally incorrect is the thought that bursts from sources in globular clusters would have a slower rise than those not in globular clusters. These misconceptions are all due to "small number games". It is interesting, however, that two series of bursts were observed from XB 1608-52 which differed significantly in burst profiles. Those bursts with a relatively fast rise and a fast decay were observed when the persistent flux was high and they exhibited a high maximum burst flux. When the persistent flux was about 5 times less, the rise times and the decay times of the bursts were larger and the maximum observed burst fluxes were reduced by a factor of about 3 (Murakami et al, 1980). An equally interesting observation was

made by Clark et al (1977). They observed a significant increase (by a factor of 5) in the persistent emission from MXB 1820-30 (in NGC 6624) and a corresponding shortening in the burst decay times (from about 4.7 sec to about 3 sec). The burst activity came to a halt while the persistent emission continued to increase.

There is little doubt that the rise time, decay time, the maximum burst flux and other features of a given burst depend on the details of that particular nuclear flash (for instance fuel composition and thermal state of the envelope; see Ayasli and Joss, 1981 and references therein). However, to date, no calculations are available that follow the evolution of burst profiles in a series of bursts. Thus no comparison can be made yet between the theory and the observed changes in burst profiles in a series of bursts from a given source.

Burst Risetimes versus "Gamma"

The quantity gamma was introduced by Van Paradijs et al (1979) and was defined as the persistent luminosity divided by the average (averaged over many bursts) luminosity at burst maximum (corrected for the underlying emission). One could redefine this (Oda, private communication) as the ratio of the persistent flux divided by the maximum burst flux in individual bursts. This way, each burst would have an associated value of gamma. If there is sometimes an apparent correlation between the risetime of bursts and the associated value of gamma (Oda, private communication), such a correlation certainly does not hold in general. The correlation, presumably valid for some data from XB 1608-52, would indicate that "fast" rises are associated with low values of gamma and "slow" rises with high values of gamma. Such a correlation is not present in data from Ser X-1 (Sztajno et al 1982) and not in data from MXB 1728-34 (Basinska et al 1982).

Are Bursts Standard Candels at Burst Maximum? - Accuracy in Source Distances

It was suggested by Van Paradijs (1978) that average bursts, at their maximum, are "standard candles". Van Paradijs was well aware of the fact that from a given source, the maximum flux in individual bursts can differ significantly. By choosing as a "standard candle" the approximate Eddington Limit of a 1.4 $M_\odot$ object with a hydrogen rich envelope (about 1.8×10^{38} ergs sec^{-1}), Van Paradijs calculated distances to individual sources and their radii. The average distance turned out to be somewhat smaller than expected from the distribution of the burst sources (Lewin et al, 1977); the average black-body radius was about 7 km. In later papers Van Paradijs (1979, 1980) increased the above "standard candle" value to about 2.7 $\times 10^{38}$ ergs sec^{-1} so that the mean burst source distances were about 9 kpc, corresponding to an average radius of the emitting regions of about 8.5 km. Thus,

Van Paradijs derived the "standard candle" value for average bursts from the "known" average distance of the burst sources.

The maximum observed flux in bursts from one source can vary by factors of about 4 (Lewin et al, 1980; Murakami et al, 1980; Sztajno et al, 1982; Basinska et al, 1982). If Van Paradijs had chosen from each series of bursts from different sources the brightest bursts (instead of the average burst), the associated "standard candle" value would have been higher by at least a factor of 2 (i.e., it would have been $\gtrsim 5.4 \times 10^{38}$ ergs sec^{-1}) and thus substantially above the Eddington limit. Using this higher value as a "standard candle" would lead to somewhat different distances for individual sources. However, since the average distance is set to be 9 kpc, the calculated average radius of the emitting regions would again be approximately 8.5 km.

Perhaps those bursts with the largest possible (not necessarily the largest observed) maximum fluxes are better "standard candles" than the average bursts or the largest observed bursts. The problem is, we do not know which bursts are the largest possible. Murakami et al (1980) observed a series of bursts from XB 1608-52 in June/July 1979 and found that a particular "maximum" flux occurred often. Thus it seemed that there was an intrinsic burst maximum. However, at an earlier occasion in April/May of the same year they observed maximum burst fluxes from the same source which were substantially larger (factor 2-3). Basinska et al (1982) analyzed 45 bursts from MXB 1728-34 observed over a 3 year period. Their data indicates that for this source a flux level of 7×10^{-8} ergs cm^{-2} sec^{-1} cannot be exceeded. Of course, one has no way of knowing that, just as in the case of XB 1608-52, this maximum level would not be different at another time (e.g. when the persistent emission is lower or higher).

The "standard candle" assumption (for either average bursts or for the largest observed bursts) is very useful in evaluating average properties of the burst sources as a class. However, if one applies it to a series of bursts from individual sources, it could lead to uncertainties in distance and thus radius of about a factor of 2 (not including a possible systematic error in the radius due to an uncertainty in the black-body assumption; see next section). If it is applied to only a small number of bursts from a given source, the uncertainty in distance and corresponding radius could be as high as a factor of 4 (the radius may have an additional systematic error due to uncertainties in the black-body assumption; see next section).

Accuracy in Radii Determinations

If radii of neutron stars could be measured with high accuracy, one could get information on the equation of state of neutron star matter (see Van Paradijs 1979). Radii determinations can be made from X-ray burst observations. In general, the observer assumes that the burst spectrum is that of a black body (there exists experimental evidence that this is approximately correct; see Swank et al 1977 and Hoffman, Lewin and Doty, 1977, page 25) and that the source distance is known (a typical number of 10 kpc is adopted). Alternatively, one can use the "standard candle" approach (see above) and estimate the distance to the source that way.

In addition to the uncertainties in distance leading to errors in the radii (see the previous section) there may be uncertainties in the black-body interpretation of the spectra. These could lead to additional systematic errors in the radii of the sources (not in their distance). I estimate that uncertainties in the black-body interpretation could lead to larger radii by a factor less than 2. Thus, distance uncertainties (see previous section) combined with the uncertainties in the black-body spectra could lead to significant uncertainties in the radii determinations for individual sources.

If one makes the assumption that the burst sources from a uniform population of neutron stars with a given mass (thus a given radius), the accuracy of the radius determination is given by the mean error in the average value which is approximately 12% (Van Paradijs, private communication). Of course, a possible systematic error due to the uncertainty in the black-body spectrum comes on top of this and may well be substantially larger (see above).

Historically the radii measurements were very important since they indicated that neutron stars were involved in the bursts (Swank et al 1977; Hoffman, Lewin and Doty 1977a, b). However, the presently available data are too inaccurate to give useful mass-radii information for neutron stars (for an additional complication see the next section).

Radius Increase Early in the Burst

The black-body radii of the emitting regions are sometimes larger (by a factor of $\gtrsim 2$) early on in the burst than during the decay portion of the burst (Swank et al 1977; Hoffman, Cominsky and Lewin, 1980; Grindlay et al, 1980; Hayakawa 1981; Cominsky, 1981). The theory can in some cases explain this; Taam (1981b) has shown that in one of his models the photosphere can expand to about 50 km due to radiation pressure. Clearly there is sufficient energy available in the flash (on the average several MeV per accreted nucleon) to lift a few percent of the accreted

material $\gtrsim$50 km above the surface of the neutron star (the depth of the potential well is about 10^2 MeV per nucleon). Taam (1981b) also found that about .01 per cent of the material accreted between bursts can be ejected. In the models of Ayasli and Joss (1981) the photosphere only expands by some ten meters or so and there is no mass loss. Mass ejection probably occurs when the luminosity at burst maximum exceeds a critical value (see next section).

Super Eddington Limit

Unless one has rather accurate knowledge about the distance to a particular burst source, it is difficult to calculate accurately the luminosity (assuming isotropic emission) at burst maximum. Distance determinations not based on the "standard candle" idea (see above) are typically uncertain by factors of 2 up to 4. This results in uncertainties in the calculated luminosities by factors 4 up to 16. Since we know (Lewin et al., 1977) that the average burst source must be at a distance of 8-10 kpc (certainly the majority of the burst sources within about 10° of the galactic center should be at this distance), one can evaluate the associated luminosities at burst maximum and it is clear that in many cases (for assumed isotropic emission), at burst maximum, the Eddington limit (of a 1.4 solar mass object with a hydrogen rich envelope) is exceeded by factors 3 perhaps in a few cases as high as 10 (Hoshi, 1981; Cominsky, 1982 and references therein; see also "Are Bursts Standard Candles..."). The theory predicts maximum luminosities near the Eddington Limit (e.g. Joss 1978; Taam 1980, 1981b; Ayasli and Joss 1981). When the luminosity exceeds a certain critical value (which can be substantially above the Eddington Limit), mass ejection will occur (see previous section). If the neutron stars have strong magnetic fields, Ayasli and Joss (1981) show that the critical luminosity can be about five times (or even more) the Eddington Limit (see below "The Role of the Magnetic Field").

Temperatures at Burst Maximum

The observed black-body temperatures near burst maximum are typically near about 30 10^6 K. Ayasli and Joss (1981) find a theoretical maximum value of 20 10^6 K which is lower than what is observed. This discrepancy is connected with the failure on the part of the present theoretical models to explain a maximum luminosity above the Eddington limit (see above). Since black-body radiation is assumed in the theory, the temperature at burst maximum (i.e., for a luminosity below or near the Eddington luminosity) as predicted by the models are consequently too low (Ayasli and Joss 1981; Taam 1981b). The discrepancy in maximum temperature between theory and observation is about a factor of 1.4. This corresponds to a factor $(1.4)^4 \simeq 4$ in maximum luminosity which is the

approximate discrepancy between the predicted theoretical maximum luminosity and the values often observed, assuming isotropic emission (see also the previous section). Ayasli and Joss (1981) have shown that strong magnetic fields (of about 3 x 10^{12} gauss) would raise the theoretical luminosity (and the temperature) at burst maximum, to the observed values (see next section).

The Role of the Magnetic Field

The role of the magnetic field in thermonuclear flashes has been discussed by Joss (1978), Taam and Picklum (1978), Joss and Li (1980) and Ayasli and Joss (1981). "Theoretical bursts" do not occur when the magnetic field is very strong ($>10^{13}$ gauss?) This is the result of "funneling" of the accreted material onto the magnetic poles and/or due to the reduction in radiative and conductive opacities in the surface layers (Ayasli and Joss 1981). It is possible that the burst sources which are of an old population (see Lewin and Joss 1981, 1982) have weaker magnetic fields than the young pulsating neutron stars in the massive binary X-ray systems. (A strong magnetic field is a requirement for the occurrence of X-ray pulsations). Joss suggested that the difference in magnetic field strengths could be the reason why "pulsars don't burst and bursters don't pulse" (see also Taam and Picklum, 1978).

Ayasli and Joss (1981) point out that strong magnetic fields (of about 3 x 10^{12} gauss) would raise the theoretical maximum luminosity by a factor of about 5 and the corresponding temperature, at burst maximum, by a factor of about 1.5. These increased values of the maximum luminosity and temperature would be close to the observed values (see also sections on "Super Eddington Limit" and "Temperature at Burst Maximum").

It seems quite likely that the bursts are suppressed at a field strength of a few times 10^{12} gauss (this is largely due to the funneling onto the magnetic poles; Ayasli and Joss, 1981). It therefore seems that such strong magnetic fields could not be the explanation for the observed high values of peak fluxes and associated peak luminosities (of several times the Eddington limit; see section "Super Eddington Limit"). One could perhaps try to argue that strong magnetic fields do not suppress the bursts (contrary to the theory) but then, of course, one loses Joss' appealing explanation for an observed fact:
"pulsars don't burst and bursters don't pulse".

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