X-ray bursts

Last time we talked about one of the major differences between NS and BH: NS have strong magnetic fields. That means that "hot spots" can be produced near the magnetic poles, leading to pulsations (this general statement is true for both rotation-powered and accretion-powered pulsars). Now we'll talk about one manifestation of another crucial difference: NS have surfaces, unlike black holes.

So far we've talked about two sources of energy associated with neutron stars: rotation and accretion. Suppose we have a neutron star that is accreting hydrogen and helium from a companion. **Ask class:** what is another potential source of energy, given that the surface temperature is typically 10^7 K? Since the accreted matter is hydrogen and helium, at such high temperatures nuclear fusion may progress. Deeper down, where the temperature and density are even higher, fusion will definitely happen. Therefore, nuclear burning is another source of energy.

Ask class: if nuclear burning happens continuously during accretion, would it be visible as another source of energy? No. The reason is that nuclear burning is much less efficient than accretion onto a neutron star. Conversion of hydrogen into helium releases a fraction $\approx 7 \times 10^{-3}$ of the mass-energy, whereas accretion onto the stellar surface releases ≈ 0.2 of the mass-energy, and the uncertainty in the accretion efficiency is a lot more than 7×10^{-3}! Therefore, if burning happens continuously, it will never be noticed.

Moving now to the observational story, starting in 1974 there were a number of detections of bursts of X-rays from different NS LMXBs. The properties varied, but typically the burst would last about 10 seconds, with a rise time that was often less than one second. The time between bursts was anywhere between hours and weeks, depending on the source. In addition, if one defined the parameter α as the ratio of the time-integrated energy in the persistent emission to the time-integrated energy in bursts, the ratio was $\alpha \sim 20 - 300$. **Ask class:** what could cause this? The total energy release in the bursts is consistent with nuclear burning. It was therefore suggested that here was an example of *unstable* nuclear burning; somehow, the fuel is stored up until some critical moment, then it all burns at once. If the burning happens rapidly, then both the rise time and the typical duration can be explained by the radiative transfer time necessary to get, respectively, the first photons out and the last photons out. Some bursts are longer: up to hundreds of seconds. This is also consistent with the nuclear flash interpretation, if one assumes that it is hydrogen that is being burned (there are weak decays involved, which slows down the process).

For relatively dim persistent sources, the luminosity can go up by a factor of ~ 100 during a burst. The luminosity is, however, limited by the Eddington luminosity. If the luminosity is much higher than that, it creates a wind of matter that streams out and

obscures the burst. This is the explanation (first proposed informally by Fred Lamb) for why it is that in high energy photon bins many bursts seem to be "double-peaked". That is, the flux rises, but when it gets high enough to eject matter, the effective radiative surface area increases dramatically (because the surface of optical depth unity is now at a much larger radius). As a result, the emission is much cooling, so although the total luminosity is still high, in the higher energies it decreases. When the luminosity goes well below Eddington, the atmosphere settles down and the high-energy emission increases.

The preceding discussion indicates that a wind of matter can be ejected during a burst. **Ask class:** considering the bulk of the matter involved in the burning, when there is a flash do you expect most of the matter to be ejected to infinity or to be bound fairly closely to the surface? The majority of the matter stays close to the surface, because the burst does not release enough energy to eject more than a small fraction to infinity (this is one consequence of the gravitational binding energy being much larger than the nuclear binding energy). **Ask class:** so what would one expect from the same situation on a white dwarf, where there is a nuclear burst? In that case, the radius is 1000x larger than a NS, so the ratio is reversed: nuclear energy dominates over gravitational energy. Therefore, in such a burst one expects the entire envelope to be ejected. This is what is thought to happen in classical novae. When the burning starts, the matter is lifted away from the surface. This decreases both the density and the temperature, so the rate of burning drops dramatically. This also means that in novae, unlike in X-ray bursts, burning is thought to be very incomplete. In X-ray bursts, the matter all burns to completion.

Instability and different burning regimes

Let's now look more closely at the instability itself. **Ask class:** in general, what does it mean that a system is unstable? It means that a slight perturbation will cause the system to change its state dramatically. **Ask class:**, so what does it mean for the nuclear burning to be unstable? It means that if there is a slight perturbation, the rate of nuclear burning will change quickly. In particular, if for some reason the temperature goes up, then for instability the nuclear burning rate must rise by enough that the temperature goes up further, leading to a runaway process.

This means, first of all, that the rate of nuclear burning must be sensitive to temperature. This is not always the case. Generically, nuclear burning requires that the wavefunctions of nuclei overlap enough for a reaction to happen. In normal thermonuclear burning (such as in stars), this happens because there is a small fraction of nuclei with enough energy to penetrate the Coulomb barrier. Let's treat this classically first. Specifically, imagine that there is some barrier energy E_b that must be overcome for the reaction to occur. If the temperature is T, then a fraction $\sim \exp(-E_b/kT)$ of the nuclei will have the required energy. If $kT \ll E_b$, this reaction is therefore extremely sensitive to the temperature, since

$\exp(-E_b/kT)$ goes up dramatically when T increases. In reality, the process is not classical, but quantum, and the actual reaction rate is dominated by quantum tunneling. In a very rough way, the effect is to lower the barrier energy (that is, a nucleus can react with a much lower energy than one would have thought classically). That's why nuclear reactions can occur in the center of the Sun ($T \approx 2 \times 10^7$ K=2 keV) even though the height of the classical barrier is $E_b \sim 1$ MeV. Qualitatively, then, **Ask class:** would one generally expect the temperature sensitivity to be greater for high or for low temperatures? It is greater for low temperatures, since the reaction rate is exponential. One way people often characterize the temperature sensitivity is by defining a "temperature exponent" ν, with the meaning that at a particular temperature T the reaction rate goes like $R \propto T^{\nu(T)}$. For example, for the CNO cycle of hydrogen burning, the temperature exponent is $\nu \approx 51 T_6^{-1/3}$.

Therefore, except at extremely high temperatures, the nuclear reaction rate goes up with increasing temperature. But how much does it have to go up? The criterion is that there is a *net* increase in temperature. However, remember that if the temperature goes up, so does the cooling rate. Therefore, the energy generation by nuclear reactions must increase faster than cooling. The cooling rate increase like T^4, so for instability in this regime it is necessary that $\nu > 4$. For CNO burning, this means $T < 2 \times 10^9$ K. Above that temperature, burning proceeds steadily; below it, in the thermonuclear regime, burning is unstable.

There is, however, another nuclear burning regime, this time *not* encountered in main sequence stars. We said earlier that the fundamental requirement for burning is that the wavefunction of nuclei overlap. This can happen at arbitrarily low temperature if the density is high enough. This is called "pycnonuclear" fusion, to distinguish it from thermonuclear fusion. **Ask class:** if this form of fusion dominates, will it be very sensitive to temperature? No, because it depends on density instead, so an increase in temperature will do little. Therefore, if the burning is in the pycnonuclear regime, burning is stable and there will be no burst.

One can therefore map out regions in (T, ρ) space for a given composition in which burning is stable or unstable. If the fuel reaches an unstable point, it will produce a burst. Global mapping of such stable and unstable regions has been done by Fushiki and Lamb (1987), and basically similar conclusions were reached by Narayan and Heyl (2003). They follow matter of some composition (usually pure helium or mixed hydrogen-helium) as it settles and is progressively buried. The temperature and density both go up, due to energy release by the settling and by burning. In addition, some of the nuclear fuel is consumed, so there is less to burn. They find that, typically, if the accretion rate is close to Eddington then burning is stable, so there will be few bursts and if there are any they'll be weak.

Quantitatively, ignition typically happens when the column depth of fuel is in the 10^{8-10} g cm^{-2} range. This is only a few tens of meters thick. That's extremely thin

compared to the 10 km radius of the star, so to a large extent one can consider this to be a plane-parallel layer.

Propagation of nuclear burning

The vast majority of analyses prior to about 1995 either more or less stopped at this point, or did numerical simulations of bursts in one dimension (radial). However, observational developments since then have changed this dramatically.

The specific development is the discovery with RXTE of brightness oscillations during X-ray bursts. Prior to the launch of RXTE in late 1995, no X-ray instrument had the time resolution necessary to detect pulsations with frequencies exceeding about 500 Hz. RXTE, however, is great at such things, and can easily detect oscillations up to 4 kHz, with a large area so the S/N is big. This led to discoveries of two major new phenomena. One is the so-called kilohertz quasiperiodic brightness oscillations, which we won't talk about here. The other is burst oscillations.

There are now more than a dozen bursting sources in which these have been detected. Specifically, what is seen is a variation in brightness, which for a given source is essentially always at the same frequency, but which has different frequencies for different sources. The frequency of variation is in the 48 Hz to 620 Hz range (with one marginal case at 1122 Hz!), depending on the source. The consistency of the frequency of these oscillations (for a given source), plus the fact that they are extremely sharp (not perfectly coherent, but $\nu/\Delta\nu > 1000$ in many cases), has led to an almost universally accepted model: once again, we're seeing emission from hot spots that is modulated by rotation. This is similar to rotation-powered and accretion-powered pulsars, leading some people to dub these "nuclear-powered pulsars".

But wait! If there are hot spots, that means that the nuclear burning is nonuniform. That means that ignition has to happen at one spot first, then spread to other parts of the fuel layer. As a result, the problem becomes more complicated: rather than simply determining when the layer is unstable, or following a 1-D burst, a full analysis has to take into account the full 3-D propagation. There are some projects underway to do this (e.g., the ASCI project at the University of Chicago), but the numerical problems are extremely tough and it is not yet possible to follow more than about the first 0.1 ms of a burst.

Incidentally, it is nowadays sometimes said that of course it was expected that the bursts would not be spherically symmetric. It is true that almost 20 years ago there were attempted simulations of 2-D bursts, but the reason often given for the expectation of asymmetry is potentially flawed despite its simplicity.

The argument goes as follows. The time between bursts is usually at least 10^4 s, but the bursts themselves last only 10 seconds and the rise time is only ~1 s. Therefore, unless

accretion over the surface is uniform to a part in 10^4, of course there will be nonuniform burning.

Suppose we imagine accretion as pouring fuel on the star, different amounts at different places. Given that ignition happens much deeper in the star than the initial accretion layer, **Ask class:** what could be wrong with the uniformity argument? To see the potential problem, imagine pouring water into a wide bowl. Even if you pour the water in only one place, it will spread so that after a while the depth of water is close to constant over the entire bowl. The same thing might happen here. Even if fuel is deposited in a highly nonuniform way, it will spread over the surface and become much more uniform. Also, remember that in order to get rotationally modulated oscillations, the burning must be not just aspherical, but nonaxisymmetric. This makes things additionally difficult, because the one obvious possible asymmetry is that if the star is rotating, the rotational equator will be different from the rotational pole. So, you could imagine that a burst would start at the equator (or the pole), but this still doesn't get you the nonaxisymmetry you need.

Ask class: what is there about the neutron star that might give a nonaxisymmetric distribution of accreted matter? Magnetic fields, as in accretion-powered pulsars. However, the inferred field strengths of 10^{8-9} G of bursters aren't nearly enough to confine the fuel as needed. Much stronger fields ($B \sim 10^{11}$ G, at least) are needed. There has been some speculation that deep, tangled subsurface fields might do the job, and since they're tangled they have high multipole moments and would not affect the matter in the accretion disk significantly. However, there is no other evidence for such fields, and they may have other problems (for example, how would they be generated? How would they survive diffusion, which will occur much more rapidly for the high-multipole components of fields?).

In summary, the burst oscillation phenomenon does seem to demonstrate that burning is nonuniform and propagates, but no one has even attempted a detailed model of this. That's important, too, because many of the specifics of how the burst oscillations occur aren't understood at all, and on their face appear to contradict the simplest ideas. There is, however, still hope that study of these oscillations will have many profound implications. For example, the light curve we observe depends on the general relativistic deflection of light, and also on the size of the star, so it may be possible (with precise fits) to determine M and R separately for individual neutron stars. You'll recall that doing such a thing will also tell us about the high-density equation of state, so this touches on fundamental nuclear physics. In addition, the propagation of nuclear burning is a phenomenon that occurs in other areas of astrophysics, most notably Type Ia supernovae. Despite current difficulties, nuclear propagation is much easier to study in X-ray bursts (where the matter is kept on the surface) than it is in an explosion like a supernova. There is long-term hope, therefore, that if we understand nuclear propagation in bursts, we can apply that knowledge to modeling of Type Ia supernovae, and from there have a better idea of the implications of supernovae

for the acceleration of the universe, Λ, quintessence, and other cool cosmological topics.

References:

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