Question 1:

Dear Cheap Astronomy – Why do supernovae explode once they start fusing iron?

Right now our Sun is fusing hydrogen into helium in its core. In maybe five billion years the situation will be all clogged up when the core has become mostly helium and the hydrogen fusion happens around it in a fusion shell. Without any further radiation pressure arising from hydrogen fusion the helium core will contract and compress and heat up which will support helium fusion creating carbon and oxygen. The combination of a helium fusing core surrounded by a hydrogen fusing shell generates a lot more energy, so the star expands outwards by radiation pressure, although being bigger, its surface will be further out from the hot core and cool down to a red colour and so our Sun will become a red giant, in about 5 billion years. But as helium fusion runs its full course, the remaining core of mostly carbon and oxygen doesn't have sufficient gravity to pull back all the expanded outer parts of the star which will just slough off as a planetary nebula and the stellar he core will keep on radiating its retained heat for billions of years without undergoing any further fusion.

But it's a whole different story for a star with about 25 times the mass of the Sun, which has much more gravity and compression and heat so that carbon in its core can fuse into neon and then the neon fuses into oxygen and then the oxygen into silicon. That very brief summary just describes the dominant fusion products of each stage and indeed oversimplifies the many different fusion pathways involved, for example oxygen is also fused straight from helium and a range of other elements such as magnesium and sulphur appear along the way, they're just not the dominant elements of each stage.

It's also the case that all this happens pretty fast. Once a giant star starts fusing carbon, the carbon is mostly used up in about 600 years, then the subsequent neon fusion is all done in about 1 year, oxygen fusion is done in about six months and silicon fusion takes about one day. It's often said that the output of silicon fusion is iron, but again that's an over-simplification. In fact this stage is generally described as silicon burning where most of the silicon photo-disintegrates due to the high energies and pressures that are in the star's core. Photodisintegration means a nucleus absorbs gamma radiation and disintegrates, mostly into alpha particles – which are essentially helium nuclei. So, it is the silicon that drives all the subsequent fusion steps, but largely by virtue of it disintegrating into helium nuclei, which then contribute to the eight reactions in the silicon burning sequence.

The full sequence is that silicon and helium fuse to sulphur, sulphur and helium fuse to argon, argon and helium to calcium, calcium and helium and titanium and helium to chromium. Chromium and helium then fuse to iron and despite what you often hear iron can and does fuse in a giant star, where iron and helium fuse to nickel and nickel and helium fuse to zinc. But really this is the last gasp of a dying star as that iron fusion and the subsequent steps do not produce new energy, indeed those last fusion reactions consume energy.

The key issue to all this is the ratio of binding energy to nucleon number, where a nucleon is a proton or a neutron – that is, the things that make up a nucleus. Protons are all positively charged, so you need binding energy in the form of the strong nuclear force to hold them together. When you are dealing with relatively-simple nuclei like helium, carbon and oxygen there are ways to reorganize the nucleons in an energy-efficient manner that produces a new element and releases energy – but once you get to iron, that principle doesn't work anymore. The formation of iron is just another fusion step, but it represents a point where so much binding energy is required to hold the newly-fused nucleus together that no nett energy is released.

So a giant star, having switched over to silicon burning has only minutes remaining as the fusion steps to iron and beyond shut down outward radiation pressure from the core so the enormous mass of the surrounding star comes crashing down. The core is crushed inwards but can only go as far as becoming an incompressible sphere of neutrons and the rebound shockwave then blows the star to bits.

Question 2:

Dear Cheap Astronomy – What are binding energies?

Technically speaking a binding energy is the amount of energy required to disassemble a system of particles. So it's actually a measurement of the amount of energy required to overcome the forces that bind particle systems together. So for example, a lot of energy is required to overcome the strong nuclear force that holds protons and neutrons together within a nucleus, then a more moderate amount of energy can separate electrons from an atom and quite small energies can readily overcome the gravitational attraction between particles.

The binding energy of most interest to astronomical people are the nuclear binding energies which underlie the process of fusion in stars. The process whereby stars fuse hydrogen involves bringing two protons and also two neutrons together to form a helium nucleus. This can't happen under normal circumstances since the positive charges of protons repel each other, but it can happen in the centre of stars where there is sufficient heat and pressure to drive protons close enough together that the strong nuclear force takes over and binds them together.

What's kind of weird is that once you have a helium nucleus, made up of two protons and two neutrons, that nucleus has less mass than two protons and two neutrons that aren't bound together. This is what's known as the mass defect and it happens in all nuclei. Why the mass defect happens is not that well understood – we just know that when neutrons and protons are bound in a nucleus some of their mass is converted to energy. So if you want to separate them again, back into unbound protons and neutrons, you have to add energy to make up for the mass defect.

During hydrogen fusion when two protons and two neutrons are jammed together, nearly all the mass defect radiates away as photons. With larger nuclei, like oxygen or carbon, fusion still produces energy but not as much – because more energy has to remain to bind the larger nucleus together, because there's that many more neighbours that have to be held together by the strong nuclear force.

So, in a very massive star, you see progressive elements being fused, but only until silicon starts fusing to iron. Once an iron nucleus is formed, all the energy from the mass defect is used up in holding the bigger nucleus together so there's no fusion energy radiation – and with the sudden loss of that outward pressure you get core-collapse supernovae. And you can go past iron to fuse even heavier elements but they will actually consume energy to produce their fusion products.

And once you get past lead, with 82 protons and 125 neutrons, the combined positive charge repulsion of all those protons in the one nucleus starts overcoming the combined strong nuclear force, meaning those nuclei begin to spontaneously break up. Many such break ups occur very quickly, but some stable heavy nuclei like thorium and uranium break down very slowly and steadily, by occasionally ejecting helium nuclei, which we also call alpha particle radiation – and they release high-energy electrons and high-energy photons, mostly gamma rays, until that heavy nucleus decays into a more stable nucleus, such as lead.

So, it turns out that iron is the only nucleus where its binding energy – that is, the energy required to break it up, is the same as the mass-energy equivalence that's required to hold its nucleus together. So, there's no energy release, either in its formation or in its break up.

If you do want to get energy out of the periodic table elements, you need to get well away from iron. For nuclei that are smaller than iron, energy arising from the mass defect is released in their formation and that energy we call fusion energy. And for nuclei that are bigger than iron, energy can be released by breaking them up, which we call fission energy. Those bigger nuclei still have an overall mass defect, where the nuclei weighs less than the individual protons and neutrons, but the energy required to keep the nucleus bound together is bigger than that mass defect. So, when you do split those big atoms, some of the released energy is used up in restoring the mass defect to the break down products, but there's still a net excess of energy released.