rich and decaying by β^- to the next higher Z element, and so on. The highest Z elements are thought to form by such neutron capture during supernova explosions when hordes of neutrons are available.

Yet at these extremely high temperatures, well above 10^9 K, the kinetic energy of the nuclei is so high that fusion of elements heavier than iron is still possible even though the reactions require energy input. But the high-energy collisions can also cause the breaking apart of iron and nickel nuclei into He nuclei, and eventually into protons and neutrons:

$$
\begin{aligned}
&{}^{56}_{26}\text{Fe} \rightarrow 13\,{}^{4}_{2}\text{He} + 4\text{n} \\
&{}^{4}_{2}\text{He} \rightarrow 2\text{p} + 2\text{n}.
\end{aligned}
$$

These are energy-requiring (endothermic) reactions, but at such extremely high temperature and pressure there is plenty of energy available, enough even to force electrons and protons together to form neutrons in inverse β decay:

$$\text{e}^- + \text{p} \rightarrow \text{n} + \nu.$$

As the core collapses under the huge gravitational forces, the tremendous mass becomes essentially an enormous nucleus made up almost exclusively of neutrons. The size of the star is no longer limited by the exclusion principle applied to electrons, but rather applied to neutrons (*neutron degeneracy*), and the star begins to contract rapidly toward forming an enormously dense **neutron star**. The contraction of the core would mean a great reduction in gravitational potential energy. Somehow this energy would have to be released. Indeed, it was suggested in the 1930s that the final core collapse to a neutron star may be accompanied by a catastrophic explosion whose tremendous energy could form virtually all elements of the periodic table and blow away the entire outer envelope of the star (Fig. 33–9), spreading its contents into interstellar space. Such explosions are believed to produce some of the observed *supernovae*. The presence of heavy elements on Earth and in our solar system suggests that our solar system formed from the debris of supernovae.

Neutron stars

Supernovae

FIGURE 33–9 These glowing filaments, observed by the Hubble Space Telescope, are remnants of a supernova whose light would have reached Earth thousands of years ago. Inside is a powerful rotating neutron star called a *pulsar*.

The core of a neutron star contracts to the point at which all neutrons are as close together as they are in a nucleus. That is, the density of a neutron star is on the order of 10^{14} times greater than normal solids and liquids on Earth. A cupful of such dense matter would weigh billion of tons. A neutron star that has a mass 1.5 times that of our Sun would have a diameter of only about 20 km.

If the final mass of a neutron star is less than about two or three solar masses, its subsequent evolution is thought to be similar to that of a white dwarf. If the mass is greater than this, the star collapses under gravity, overcoming even the neutron exclusion principle. Gravity would then be so strong that even light emitted from it could not escape—it would be pulled back in by the force of gravity. Since no radiation could escape from such a star, we could not see it—it would be black. An object may pass by it and be deflected by its gravitational field, but if it came too close it would be swallowed up, never to escape. This is a **black hole**.