The correct answers are written in **bold, italic and underlined**.

The most important questions to study for the exam are **highlighted**.

1. What is believed to be the usual process that causes the actual explosion in a type II supernova (massive star exploding)?
   - Explosive nuclear reactions begin in the core when the central temperature reaches about $10^9$ K, disrupting the entire star.
   - **The core collapses inward gravitationally until it has the density of an atomic nucleus and then rebounds. The envelope collapsing against this rebounding core then explodes outward.**
   - The core collapses inward gravitationally to become a black hole. The envelope collapsing inward toward this black hole is heated to the point that catastrophic nuclear reactions begin in it, explosively ejecting the envelope.

   The envelope collapsing against this rebounding core generates a shock wave that disrupts and ejects the envelope in a supernova explosion. The impact from the infalling envelope halts the core rebound, and the core remains behind as a neutron star.

2. The brightness of a supernova just after the explosion is equivalent to
   - the output of about 1000 stars similar to our Sun.
   - the total output of all the stars in a typical globular cluster, about $10^6$ stars.
   - **the total output of all the stars in a typical spiral galaxy, more than $10^{11}$ stars.**

   A supernova can easily outshine the galaxy in which it resides, for a few days.

3. Observations of supernovae in distant galaxies similar to our own Milky Way suggest that they occur at the rate of one every 20 years per galaxy. The last recorded supernova in our Galaxy was by Kepler in 1604, almost 400 years ago. Why is this?
   - The disk of our Galaxy, and particularly its dense center, is hidden from us on the Earth because of the tilt of the Earth's spin axis and the alignment of the Earth's orbit.
   - **Most supernovae have occurred in the disk of our Galaxy, and our view of this disk is obscured by dense dust and gas clouds. Consequently, we have not seen the majority of supernova explosions that have occurred in the Milky Way.**
   - Our Galaxy is different from other spiral galaxies in that the stars are old. No new stars that could evolve into supernovae have been formed in recent times.

   Our view within the disk of our Galaxy is limited to 10,000 light-years or so by dense dust clouds.

4. What are cosmic rays?
• **Atomic nuclei and other subatomic particles striking the Earth's atmosphere from space**
  • Beams of light emitted by rotating neutron stars that sweep past the Earth like lighthouse beams
  • Bursts of X rays from neutron stars in binary star systems

Cosmic rays are made up primarily of atomic nuclei that travel through space after being accelerated to very high speeds and energies, often by processes associated with supernovae.

5. What is believed to be the origin of most of the cosmic rays arriving at the Earth from outside the solar system?

• **The interaction region between an expanding supernova remnant and the surrounding interstellar medium**
  • Charged particles accelerated in the intense electric and magnetic fields of rotating neutron stars
  • High-energy processes in the hot and turbulent gas during a supernova explosion

Although the highest-energy cosmic rays appear to originate in external galaxies, most of the intermediate-energy cosmic rays are believed to arise when the expanding gas in a supernova remnant slams into the surrounding interstellar medium.

6. What was unusual about supernova 1987A in the Large Magellanic Cloud?

• **The star that exploded was a blue supergiant.**
  • The explosion resulted from mass transfer onto a white dwarf in a binary star system.
  • The explosion released a burst of neutrinos.

Most of the massive stars that explode (type II supernovae) are red supergiants.

7. Supernova 1987A was a relatively nearby and very well-observed supernova. Which of the following was NOT observed in connection with this supernova?

• Neutrinos produced during core collapse
• **Pulsed radiation from a rotating neutron star after the explosion**
• The original star before it exploded

Such a pulsar is expected from a Type II supernova (massive star exploding), but none has yet been observed.

8. A burst of neutrinos was observed from Supernova 1987A. How were these neutrinos detected?

• By X rays that were produced when the neutrinos struck nuclei of iron and nickel inside special detectors
• **By Cherenkov radiation that was produced by particles traveling faster than light inside special detectors**
By argon atoms produced when the neutrinos struck chlorine nuclei in a special tank of carbon tetrachloride

The neutrinos strike water molecules inside the detector and produce high-speed electrons. While no particle can travel faster than the speed of light in a vacuum, these electrons move through the water faster than the speed of light in water, and consequently produce Cerenkov radiation.

9. What causes a Type I supernova?
   - In a binary star system, a giant star filling its Roche lobe dumps gas onto a white dwarf, bringing the white dwarf up to the Chandrasekhar mass limit.
   - The core of a massive star is gradually transformed into iron by thermonuclear fusion reactions until it collapses, causing the outer layers to explode off the star.
   - Helium shell flashes push the outer layers of an asymptotic giant branch star out into space, leaving behind a stellar remnant.

Type I supernovae involving a white dwarf exploding can occur only in a binary star system where mass transfer increases the mass of the white dwarf.

10. What kind of star produces a neutron star?
   - Only high-mass stars
   - Only low-mass stars
   - All masses of stars

Neutron stars have masses from 1.4 to 3 solar masses and are the collapsed cores of high-mass stars. Low-mass stars end their lives as white dwarfs, not neutron stars. The maximum mass of a white dwarf is 1.4 solar masses, so even if a white dwarf explodes as a Type I supernova, it cannot form a neutron star.

11. What force keeps a neutron star from collapsing to a black hole under its intense self-gravitational field?
   - Neutron degeneracy pressure, the quantum-mechanical effect in which no two neutrons with the same properties can occupy the same space
   - The very high temperature and velocity of the neutrons, which create a thermal gas pressure to oppose gravity
   - The intense nuclear repulsion between neutrons, only felt when these neutrons are very closely packed because the nuclear force is very short-ranged

Neutron stars are held at their present radius by degeneracy pressure of the closely-packed neutrons.

12. When was the existence of neutron stars first predicted?
   - Never. They were discovered observationally before anyone predicted their existence.
   - 1933
   - 1967
Within a year of the discovery of neutrons by the English physicist James Chadwick in 1932, two American astronomers, Fritz Zwicky and Walter Baade, predicted the existence of neutron stars.

13. Who made the first discovery of a pulsar?
   • Fritz Zwicky and Walter Baade
   • Jocelyn Bell
   • Albert Einstein

Jocelyn Bell was a graduate student at Cambridge University and detected pulses of radio waves from one specific location in the sky. These pulses arrived with a precise period of 1.337301 seconds.

14. What is the composition of a pulsar?
   • Entirely protons, their mutual electrostatic forces opposing the gravitational attraction
   • Almost entirely neutrons
   • Equal numbers of closely packed neutrons and protons, similar to a giant nucleus

Neutron degeneracy pressure supports the matter against collapse under gravity.

15. How does a pulsar pulse?
   • A high-angular-momentum (rapidly spinning) black hole pulsates and sends out regularly spaced pulses of electromagnetic radiation.
   • A rapidly spinning, magnetized neutron star emits light and radio waves along its magnetic axis.
   • A white dwarf in a binary star system is periodically eclipsed by its companion star.

The beams of light and radio waves sweep around the universe like giant lighthouse beams. If they sweep past the Earth, then we detect one or perhaps two pulses every rotation.

16. What physical mechanism has produced the very rapid rotation rate of a neutron star in the center of a supernova explosion?
   • Explosive expansion of the supernova has transformed the slow rotation of a massive star into rapid rotation, as a consequence of the conservation of angular momentum.
   • Rapid implosion of a slowly rotating mass into a much smaller volume causes the conservation of angular momentum to result in high rotation speed.
   • Intense radiation pressure on the imploding stellar core from the supernova explosion spins this core up to high rotation speeds as a consequence of the conservation of energy.
Contraction of the mass toward its rotation axis will lead to speed-up of rotation because of the conservation of angular momentum.

17. What is the mechanism that produces the continuous series of narrow pulses of electromagnetic radiation at precise rates from neutron stars or pulsars in our universe?
   - The rapid orbiting of a neutron star around a black hole, the intense gravitational field of which periodically focuses emitted electromagnetic radiation from the neutron star toward the Earth
   - **The regular passage across the Earth of a narrow, directed beam of electromagnetic radiation from a very compact and rapidly rotating neutron star**
   - The regular ringing or oscillation of the solid surface of a very compact neutron star, in the manner of a ringing bell or a vibrating wine glass

The intense magnetic fields of neutron stars produce focused beams of radiation that sweep the sky like lighthouse beams.

18. In a normal pulsar such as that in the Crab Nebula, what mechanism produces the "lighthouse beams" that sweep across the Earth to create pulses of light and other radiation?
   - Radiation from a hot spot on the surface of the rotating neutron star, created by matter striking the surface after being pulled from a companion star
   - A crack or fissure in the surface of the rotating neutron star that allows radiation to escape from the extremely hot interior
   - **Charged particles such as protons and electrons being accelerated by intense electric and magnetic fields around the rotating neutron star**

The rotating magnetic field acts like an immense electric generator and drives charged particles along the magnetic field lines. These accelerated charges radiate electromagnetic waves such as light waves in a narrow beam that sweeps around the sky like a lighthouse beam.

19. Pulsars, or rotating neutron stars, emit a series of pulses whose pulsation rate is
   - **slowing down with time as a consequence of the loss of energy as radiation and the conservation of energy.**
   - speeding up as the neutron star is slowly being compressed into a smaller volume by its intense gravitational field.
   - absolutely constant, as expected for an isolated spinning object with a superconducting shell around a superfluid core.

Pulsars are slowing down as they lose energy, apart from sudden but small speed-up events called glitches.

20. A single pulsar (not a member of a binary system) is observed to be rotating at the rapid rate of 40 times per second. What does this tell us about the pulsar?
   - It will soon collapse to form a black hole.
- **It is a young pulsar.**
- It is an old pulsar.

Pulsars slow down because they lose energy through the emission of beams of particles. A rapidly spinning single pulsar (one that cannot have been spun up by mass transfer from a companion) must therefore be young.

21. The "spin-up" mechanism that has resulted in pulsars with abnormally high rotation rates (rotating hundreds of times per second) is thought to be
- the ejection of matter along the two opposing beams of the neutron star, the conservation of angular momentum resulting in more rapid rotation of the remaining mass.
- starquakes that redistribute angular momentum in the neutron star.
- **mass transfer from a companion star in a close binary system.**

Mass transfer through the Roche lobe of a binary system will be directed so as to speed up the rotation of the pulsar.

22. "Gold! Gold! I'm rich!!" This was a stock line in many early movies and comic books—but where did the gold come from? (Gold is heavier than iron.)
- **From colliding neutron stars**
  - From runaway nuclear reactions in the collapsing cores of massive stars during the supernova explosions at the end of their lives
  - From core nuclear reactions during the "normal" lives of massive stars, subsequently thrown into space by supernova explosions

It is believed that processes during the supernova itself cannot build up the amount of heavy elements that we see around us and that a significant portion is created collisions between neutron stars.

23. Pulsating X-ray sources in space are thought to be binary star systems containing an ordinary star and
- a black hole.
- a spinning white dwarf star.
- **a spinning neutron star.**

The characteristics of the X-ray emission indicate that normal matter falling onto the neutron star from the ordinary star is heated to the point where it emits X rays.

24. What mechanism is believed to produce the regularly spaced pulses of X-ray radiation that we observe from some parts of the sky?
- Matter being accelerated toward a neutron star from a companion star emits a beam of X rays as it falls inward; this beam sweeps around the universe as the two stars revolve around each other.
- **Matter falling onto a rotating neutron star from a companion star creates hot spots that emit X rays.**
• Charged particles moving along the lines of magnetic force near the poles of a rotating neutron star emit X-ray beams that sweep around the universe.

The matter falls along the magnetic lines of force, creating hot spots near the poles of the neutron star, and the hot spots swing alternately into and out of view as the neutron star rotates.

25. What mechanism is responsible for X-ray bursters?
• **Matter falling onto a neutron star from an orbiting companion star in a binary system**
• Instabilities in the magnetic field of a rotating neutron star
• We don't know

Hydrogen from a companion star falls onto the neutron star and is promptly converted to helium by thermonuclear fusion. The resulting layer of helium is degenerate and explodes when thermonuclear fusion reactions begin in it.