ANSWER KEY

Section 1: Stellar Evolution & Type 1a Supernovae (61 points total, with 1 bonus point)

1) Iron
2) Chandrasekhar limit
3) B (1 bonus point for 716 rotations/second)
4) Spiral arms
5) The CNO cycle is a fusion reaction (1 point) that mainly stars of greater than 1.3 solar masses (1 point) use to convert hydrogen into helium. Proton-proton chain reactions are more important in stars with less mass (1 point). The cycle involves carbon, nitrogen, and oxygen acting as catalysts for four protons to fuse and produce an alpha particle (1 point), as well as two positrons and two electron neutrinos (1 point). The positrons immediately annihilate with some electrons and release gamma rays (1 point) while the neutrinos escape and take away some energy (1 point). This process is called a cycle because one nucleus goes through multiple reactions and becomes carbon, nitrogen, and oxygen in an endless loop (1 point).
6) Carbon, neon, carbon-oxygen
7) B (1 point); The energy in B-class stars is mostly formed from the CNO cycle (1 point), which is very sensitive to temperature changes (1 point). Because it is sensitive, the energy generation is concentrated near the core of the star, resulting in a convection zone around the core (1 point).
8) Unlike main sequence stars, which gradually expand as their temperature increases, white dwarfs do not increase in volume (1 point) because the electron degeneracy pressure is not affected by temperature (1 point). They are unable to control the fusion reactions (1 point), so the reactions occur very quickly. In a matter of a few seconds, many heavy elements are created in the core (1 point), which greatly raises the core temperature, and causes the material to be ejected away in a type 1a supernova explosion at very high speeds (1 point).
9) During the thermally pulsing asymptotic giant phase, the helium shell of a star has run out of fuel (1 point), so the fusion of a thin outer shell of hydrogen provides energy (1 point). Over time, the helium derived from fusing hydrogen builds up and ignites in helium shell flash (1 point: must mention helium shell flash), which causes the star to expand and cool. The hydrogen shell burning is shut off (1 point), and there is strong convection between the two zones (1 point). When the helium burning approaches the hydrogen shell, the hydrogen shell is reignited and the process begins again (1 point). This process is a thermal pulse (1 point).
10) Population III stars were the first stars to evolve after the creation of the universe (1 point), and so they were very poor in metals (1 point). This allowed them to have stellar masses hundreds of times that of the sun (1 point). Thus, they evolved very quickly (1 point), and exploded in pair-instability supernovae (1 point).
11) Center
12) D
13) Schwarzschild radius
14) AM Canum Venaticorum system (1 point); outbursting state (1 point)

15) AM CVn variables can form with a white dwarf donor (1 point). In this case, a binary system of a white dwarf and low-mass giant (1 point) goes through common envelope evolution (1 point), which results in double white-dwarf binary (1 point). The binary orbit shrinks due gravitational radiation (1 point), and when it has shrunk to about five minutes (1 point), the less massive of the white dwarfs will begin mass transfer to its companion when it fills its Roche lobe (1 point: must mention Roche lobe). In a second case, AM CVn can form with a helium star companion (1 point). The giant in the common envelope evolves into a helium star (1 point) instead of another white dwarf, and is more expanded than a white dwarf. It fills its Roche lobe first (1 point) when the stars are brought into contact with gravitational radiation and starts mass transfer with an orbital period of about 10 minutes (1 point). In the third case, the companion is a terminal-age main sequence star (1 point). There is no common envelope, and the companion instead fills its Roche lobe near the end of main sequence (1 point). As more angular momentum is lost from magnetic braking (1 point: must mention magnetic braking), the orbital period of the system shrinks (1 point). The evolved main sequence star begins transferring matter to the white dwarf, forming an AM CVn system (1 point).
16) Mira
17) Instability strip
18) Mira
19) Main sequence
20) T Tauri
21) RR Lyrae

Section 2: Deep Sky Objects (91 points total, with one point for each answer unless otherwise specified, and total point values for each question listed next to first answer)

22) NGC 2392 (5 points)
    a) Eskimo Nebula, Caldwell 39, Clownface Nebula (1 point for each listed)
    b) Planetary nebula
23) SNR 0509-67.5 (8 points)
    a) Silicon & iron (1 point for each)
    b) Type 1a supernova
    c) Light from the supernova was reflected off of interstellar dust, which delayed its arrival to earth.
    d) Light echo
    e) Optical & x-ray (1 point for each answer)
24) Tycho's SNR (8 points)
    a) November 1572 (2 points if November is specified, 1 point if only 1572)
    b) Type 1a supernova
    c) G2
    d) The appearance of this supernova helped revise ancient models of space (1 point), and it also led to more accurate cataloguing of stars (1 point).
    e) X-ray
25) Mira or Omicron Ceti (10 points)
    a) Binary star system

b) Mira A is in the thermally pulsing AGB phase (1 point), and each pulse lasts more than a decade with about 10,000 years between pulses (1 point). Mira increases in luminosity with every pulse cycle (1 point), and the pulses continue to grow stronger (1 point). This causes Mira's instability in luminosity and size over short periods of time (1 point).
c) Infrared
d) Left: visible; Right: ultraviolet (1 point each)

26) SN 2011fe (7 points)
a) Palomar Transient Factory survey
b) Type 1a supernova
c) Because SN 2011fe was first observed in a very early stage (1 point), astronomers will be able to determine its composition during and evolution through the whole supernova explosion (1 point). This will allow for more accurate calculations and distances to other type 1a supernova as well (1 point).
d) Ultraviolet

27) NGC 2440 (4 points)
a) HD 62166 (1 point); This star is possibly the hottest known white dwarf (1 point).
b) The planetary nebula's complex structure suggests that flow from the white dwarf at the center has been periodically directed in opposite directions.

28) SNR G1.9+0.3 (5 points + 1 possible bonus point)
a) Type 1a supernova remnant
b) This SNR is the youngest ever discovered in the Milky Way Galaxy (1 point). (1 bonus point if they specify it is estimated to be 110 years in age.)
c) Left: radio; Right: x-ray (1 point each)

29) Henize 2-248 (7 points)
a) Planetary nebula and two white dwarfs (1 point for each answer)
b) Scientists initially studied this nebula to try to understand how it developed its abnormal shape (1 point)
c) Super-Chandrasekhar double-degenerate system (or any other answer detailing that it is a binary white dwarf system which is above the Chandrasekhar limit) (1 point)
d) Type 1a supernova; 700 million years (1 point for each answer)

30) J 0751 and J 1741 (object has multiple names, as long as it includes this part of the name then it is sufficient) (8 points)
a) Abbreviation: AM CVn; Full name: AM Canum Venaticorum; these are binary star systems wherein a white dwarf star takes mass from its partner (3 points, one for each name and one for description)
b) J 0751: ratio of ~0.2 (0.19 solar masses and 0.97 solar masses); J 1741: ratio of ~0.1 (0.12 solar masses and 1.11 solar masses) (2 points, 1 point for each DSO's answer)
c) These objects were observed in the visible and x-ray wavelengths (2 points, 1 for each wavelength)

31) Any of the following: Stingray Nebula, SAO 244567, Hen 3-1357, Henize 3-1357 (6 points)
a) The red is gas which is heated by the central star's winds
b) This is the youngest planetary nebula known (1 point), and has a remarkably rapid evolution (1 point)

c) The effective temperature of the nebula peaked in 2002 (1 point) at 60 kK (60,000 K) (1 point)

32) Sirius A and B (8 points)
   a) Sirius A releases 26 times as much energy as our Sun.
   b) The existence of Sirius B was predicted by Bessel in 1844. It was first observed in 1862 by Alvan Clark (4 points: 1 point for each answer)
   c) Oxygen and carbon (2 points)

33) HM Cancri or RX J0806.3+152 (7 points)
   a) 321.5 seconds (5.4 minutes); It is the shortest orbital period of any binary system discovered.
   b) Xray
   c) The observation of such systems pushes to the limit of current technology because they are so dim that only the largest telescopes can sense them.
   d) Approximately one ton (~.5 solar masses are forced into an Earth-like volume so these stars are very dense)
   e) The Evolved Laser Interferometer Space Antenna is a proposed telescope which would be able to detect the predicted gravitational waves being emanated from this system.

34) SS Cygni (8 points)
   a) 372 light years
   b) 520 light years; the period of the star's fluctuations did not match with the predicted distance (2 points)
   c) Cataclysmic
   d) Cataclysmic variable stars are binary systems in which one white dwarf accretes mass from another star. (1 point). When the accretion reaches a certain point, runaway hydrogen fusion reactions occur (1 point). This causes the system to ignite for some time in a nova, and this process repeats over time (1 point).

Section 3: Calculations and Math-Related Questions (13 points total)

35) 1.70e+25 kilograms (3 points)

36) An exoplanet is orbiting a star once every 4 days. The eccentricity of its orbit is 0.6, and the semimajor axis is 0.05 AU. (For each problem except for the circumference, work is worth 1 point, and the answer is worth 1 point: 10 points total)
   a) Calculate the semiminor axis (2 points):

$$\mathrm{e} = \frac{\sqrt{a^2 - b^2}}{a}$$

$$0.6 = \frac{\sqrt{0.05^2 - b^2}}{0.05}$$
$$0.03 = \sqrt{0.05^2 - b^2}$$
$$9 \cdot 10^{-4} = 0.05^2 - b^2$$
$$b^2 = 0.0025 - 0.0009$$
$$b^2 = 0.0016$$
$$b = 0.04$$

b) 2 points for calculating average radius: $Er \approx Er_q = \sqrt{\frac{a^2 + b^2}{2}}.$; average radius = 6.77e+9 meters

c) 2 points for calculating circumference of orbit (no work needed): C ~ 0.28 AU ~ 4.1887e+10 meters

d) 2 points for calculating velocity of planet: 45 days = 3.888e+6 seconds; velocity = m/s = 10773 m/s

e) 2 points for calculating orbital period: 3.04e+5 seconds, 3.52 days