Answer Key

1. (a) ESO 137-001
   (b) 3
   (c) ram pressure stripping
   (d) P
2. (a) globular cluster
   (b) turn off point
   (c) age of the cluster
3. (a) RR Lyrae
   (b) K
   (c) globular clusters
   (d) 5, 15
   (e) Tuc 47 (Tucanae 47)
4. (a) 10, M82 (Cigar Galaxy)
   (b) SN2014J, Type Ia SNR
   (c) 25
5. (a) Cepheid variable
   (b) H
   (c) 18, 24
   (d) 13, M100 (NGC 4321)
   (e) A (Population I Cepheid)
6. (a) Antennae galaxies
   (b) Star forming regions
   (c) material infalling on black holes/neutron stars
7. (a) Centaurus A (Cen A or NGC 5128)
   (b) all of them (a through e)
   (c) 32
   (d) only emission lines for new star formation no absorption lines for general stars
   (e) merger of 2 normal galaxies
8. (a) D, B, A, C
9. (a) 3C 75, NGC 1128 or (Abell 400)
   (b) pair supermassive black holes
   (c) merge into one black hole
   (d) gravitational waves
   (e) NGC 4993
10. (a) M51 (Whirlpool galaxy)
    (b) ULXs (ultraluminous X-ray sources)
    (c) neutron stars
    (d) none
11. (a) 16
    (b) star formation regions
    (c) A, more E taking place at 8 microns
12. (a) 6
    (b) radio, X-ray
    (c) jets
    (d) shock wave
13. (a) The Phoenix Cluster
    (b) radio jets from supermassive black hole
    (c) cooling and condensing
    (d) increases star formation
14. (a) GW 170817
    (b) gravitational waves
    (c) X-rays
    (d) short gamma ray burst radiation
15. (a) rotational velocity and luminosity of spiral galaxies
    (b) 30
    (c) relative distance between sets of galaxies
    (d) Cepheids
16. (a) IC 10
    (b) X-ray binaries
    (c) gravitational waves
17. (a) SPT 0346-52
    (b) no radio or X-ray emissions
18. (a) Chandra Deep Field South
    (b) biggest black holes growing faster than the rate of star formation in the galaxies they inhabit

19. (a) Antennae galaxies
    (b) The average number of **photon counts**. Specifically, the mean of the photon counts over all the pixels within the box at the given x-value.
    (c) **Logarithmic**. Astronomical energies span many **orders of magnitudes**; a logarithmic scale will get a sampling of all these different orders of magnitude.
    (d) Visible
    (e) **Yes**. The dark region is a large swath of dust and cold gas which is obscuring a site of intense starburst. It absorbs the new stars' high energy light (including visible wavelengths) and **re-emits the absorbed energy as infrared**. So it would appear dark in visible light and bright in infrared.

20. (a) 42.2 solar masses
    (b) 2.89×10^5 to $2.89 \times 10^8 K$
    (c) **No.** Although there's more gas, the **inner part is hotter**, and since the luminosity is dependent on T^4, the temperature overcompensates for the lack of radiating material. The inner part is therefore more luminous.

21. (a) 780,000 pc $\pm$ 100,000 pc
    (b) 1.58 (reciprocal 0.63 for half credit)
    (c) **Yes**, the original estimate was probably an underestimate since this was likely a **double-degenerate** scenario.
    (d) 12.4 Mpc $\pm$ 1 Mpc
    (e) Approximately 10^9

22. (a) Both the temperature and luminosity decrease.
    (b) Curve A
    (c) It takes time for white dwarfs to cool and become that dim. At the age represented by Curve A, the white dwarfs in this galaxy haven't cooled as much, but at the age represented by Curve B, they've had the time to cool much more. Since the luminosity of an object is proportional to T^4, a lower temperature would mean a dimmer white dwarf.
    (d) The cooling rate slows as the white dwarf cools (the graph of temperature vs. time would appear to be concave up and decreasing), until crystallization sets in. This causes the amount of white dwarfs at that luminosity to "build up"

23. (a) Greater than 1
    (b) Higher surface gas density results in a higher chance for higher mass clumps that can exceed the Jeans mass, which would lead to runaway contraction and heating, marking the beginning of star formation. Based on this, we would expect starburst galaxies to have higher gas surface densities.
    (c) In normal disk galaxies, the relationship between the FIR luminosity and the SFR is complex because stars with a variety of ages can contribute to the dust heating, and only a fraction of the bolometric luminosity of the young stellar population is absorbed by dust. However, in starburst galaxies, the physical coupling between the SFR and the IR luminosity is much more direct. Young stars dominate the radiation field that heats the dust, and the dust optical depths are so large that almost all of the bolometric luminosity of the starburst is reradiated in the infrared.
    (d) i. The extinction in most star forming regions is so large that one expects part of the ionizing radiation from the starburst to be absorbed by grains, and in some objects, extinction of Brγ itself is probably significant, making it seem dimmer, and as a result, less active (star formation wise) than it actually is.
        ii. If the starbursts are observed after the peak of the burst, then the dust heating is dominated by longer lived stars and the effect of the Brγ emission line is less than it actually was.

24. (a) We would see the break at 91.2 nm. Any photon emitted with wavelength shorter than the Lyman Limit (91.2 nm) be completely absorbed by hydrogen gas both in a galaxy and along the line of sight to us instead of reaching our telescopes, resulting in a "break".
    (b) Galaxy A: 3.1-3.5; Galaxy B: 4.1-4.5. Galaxy B is further away.
    (c) The galaxy's spectrum would have a break in the UV region at 91.2 nanometers, as specified in (a). However, the Earth's atmosphere is extremely opaque at these wavelengths, so we would not be able to see anything. The reason we can see the breaks for these distant galaxies is because they have been redshifted to wavelengths that we can see through the Earth's atmosphere. Since these galaxies in this part are nearby, this cannot be the case.
    (d) 3650-4100 Mpc