21. Galaxy Evolution

> *Reality provides us with facts so romantic that imagination itself could add nothing to them.*
>
> Jules Verne (1828 – 1905)
> French science fiction author

Agenda

- Announce
  - Tests/Black numbers
  - HW2 – Black Hole tutorial
  - Solar Eclipse Tomorrow…in Libya
- The Monty Hall Problem
- Ch. 21
- Hubble's Law Lab

The Monty Hall Problem/Paradox

- There are three doors. Behind one door is a million dollars you win if you pick that door.
- You get to pick a door (but do not open it yet).
- However, after you do so, the MC (Monty Hall) opens one of the other doors to show that it is not the winning door. S/He then offers you the chance to switch to the other closed door.

- Should you do so?

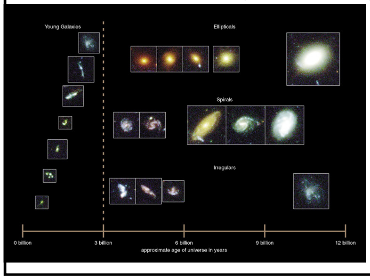
21.1 Looking Back Through Time

Our goals for learning:

- What do we mean by galaxy evolution and how do we study it?

Galaxy Evolution…

- …is the study of how galaxies form and how they change over time.
- As was the case with stars…
  - we can not observe an individual galaxy evolve
  - but we can observe different galaxies at various stages of their life cycles



- This is made easier by virtue of lookback time.
- We can plot a "family album" for each type of galaxy.
- The greater the redshift...
  - the younger the galaxy!

21.2 Galaxy Formation

Our goals for learning:

- What two starting assumptions do we make in most models of galaxy formation?
- Describe in general terms how galaxies are thought to have formed.
- What does careful study of our Milky Way Galaxy tell us about galaxy formation?

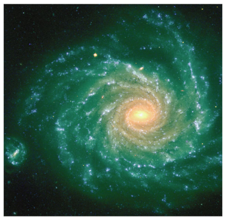
Modeling Galaxy Formation

- With our current telescope technology…
  - we are unable to see back to the time when galaxies first formed
  - we must rely on theoretical (computer) models to describe how galaxies formed
- The following assumptions are made when constructing these models:
  1. the Universe was uniformly filled with Hydrogen & Helium gas for the first million years after the Big Bang
  2. this uniformity was not quite perfect; some regions of the Universe were slightly denser than others
- All of the H & He gas expanded with the Universe at first.
  - after about a billion years, the denser regions slowed down and began to collapse under self-gravity
  - the collapsing gas became **protogalactic clouds**

Modeling Galaxy Formation

- As a protogalactic cloud collapses, at first it radiates away its gravitational potential energy.
  - it gets colder
  - stars begin to form in the coldest, molecular cloud cores
  - same physics as when ionized and atomic ISM condenses into molecular clouds and forms star in the star-gas-star cycle of the Milky Way

- Next clue comes from galaxy colors
  - the spheroidal component is red
  - the disk component is blue/white
- Conservation of angular momentum
  - caused remaining gas to rotate faster and flatten…star formation continues in disk
  - with no gas left in the spheroid, no new stars are formed and only old, red stars remain



Modeling Galaxy Formation

(a) **A protagalactic cloud contains only hydrogen and helium gas.**

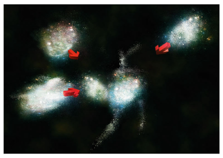
(b) **Halo stars begin to form as the protogalactic cloud collapses.**

(c) **Conservation of angular momentum ensures that the remaining gas flattens into a spinning disk.**

(d) **Billions of years later, the star–gas–star cycle supports ongoing star formation within the disk. The lack of gas in the halo precludes further star formation outside the disk.**

The Milky Way Provides Clues

- Studying the halo stars in our own Milky Way provides data for our models.
  - random orientation of stellar obits implies that halo stars formed before the protogalactic cloud collapsed into a disk
    - stars which formed in the disk orbit on the same plane in the same direction
  - low content of heavy elements in halo stars implies that they formed before the star–gas– star cycle could significantly enrich the ISM
- However, heavy-element content of halo stars does not simply decrease with distance from the Galactic center.
  - implies that halo star formation did **not** begin in a single protogalactic cloud



- There must have been a few smaller clouds where…
  - stars had already begun to form
  - they collided to form a larger protogalactic cloud
- Remaining key questions:
  - where is the very first star generation?
  - what caused the density enhancements in the early Universe?

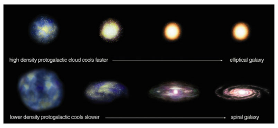
21.3 Why do Galaxies Differ?

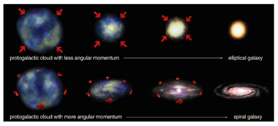
Our goals for learning:

- How might a galaxy's birth properties have determined whether it ended up spiral or elliptical?
- How might interactions between galaxies cause spiral galaxies to become elliptical?
- What do observations of galaxy clusters tell us about the role of galaxy interactions?

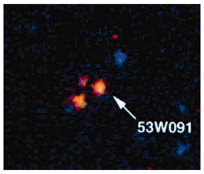
What Determines Galaxy Type?

- We can explore two options:
  - the initial conditions of the protogalactic cloud; i.e. destined from birth
  - later interactions with other galaxies; i.e. a life-altering conversion
- Two plausible explanations regarding the birth properties of the protogalactic cloud:
  - Protogalactic spin…the initial angular momentum determines how fast the cloud will form a disk before it is completely turned into stars
  - Protogalactic cooling…the initial density determines how fast the cloud can form stars before it collapses into a disk

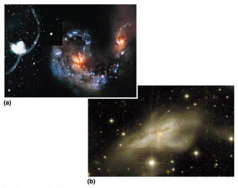




What Determines Galaxy Type?

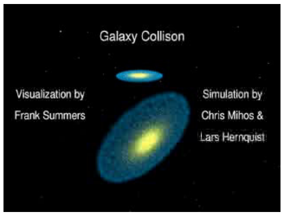


- This giant elliptical provides evidence for the protogalactic cooling explanation.
  - it is very distant (young) and very red, even accounting for redshift
  - white and blue stars are missing
  - star formation has ceased very early in the galaxy's history
  - no gas will be left to form a disk
- Galaxy Interactions
  - when two spiral galaxies collide
  - tidal forces randomize the orbits of stars
  - gas either falls to the center to form stars
  - or it is stripped out of the galaxies
  - the disk is removed
- The galaxy becomes an elliptical.



When Spirals Collide

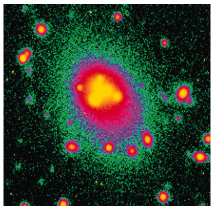
Model of Galaxy Interaction



Movie. Click to play.

The Role of Galaxy Clusters

- Galaxy clusters provide evidence that some galaxies are shaped by interactions:
  - elliptical galaxies are more common in cluster centers
  - collisions will occur more often in crowded cluster centers
  - **central dominant (CD) galaxies** are gigantic ellipticals found in cluster centers
  - they grow large by consuming other galaxies



- These CD galaxies often contain tightly bound clumps of stars.
- They are probably the leftover cores of galaxies which were *cannibalized* by the CD.
- Some CD galaxies are more than 10 times as massive as the Milky Way.
  - making them the largest galaxies in the Universe!

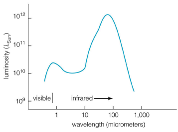
21.4 Starburst Galaxies

Our goals for learning:

- What is a starburst galaxy?
- How do we know that a starburst must be only a temporary phase in a galaxy's life?
- What can cause starbursts?

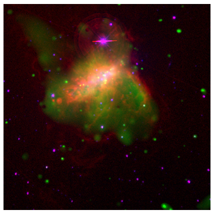
Starburst Galaxies

- An average of 1 new star per year forms in the Milky Way.
- We observe some galaxies with a star-forming rate of 100 per yr.
- We call them **starburst galaxies**.
  - infrared image of Arp 220 ⟶



- They look normal in visible light (10^{10} $L_\odot$ like Milky Way).
  - but they are 100 times brighter in infrared light
  - molecular clouds block the visible/UV light from new stars
  - dust in the clouds absorbs this light and reemits the energy as infrared light
- With such a fast rate of star formation, the galaxy will use up its gas..
  - in only a few 100 million years
  - starburst phase is temporary in light of fact that galaxy is billions of years old

Starburst Galaxies



- 100 times star-forming rate also means 100 times supernova rate.
  - ISM is full of hot superbubbles
  - supernovae continue to pump energy into the superbubbles
- The hot (10^7–10^8 K) gas breaks out
  - and a **galactic wind** streams from galaxy
  - ⟵ NGC 1569 (X-ray–green; visible–red)
- Starburst galaxies are irregular in type.
  - lots of dusty molecular clouds and usually two distinct clumps of stars
- This suggests that the starburst is caused by the collision of two spiral galaxies.
  - although a close encounter could trigger starburst, e.g. Large Magellanic Cloud

21.5 Quasars and Other Active Galactic Nuclei

Our goals for learning:

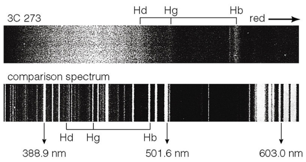
- What are active galactic nuclei and quasars?
- The nature of quasars was once hotly debated. What evidence supports the idea that they are the active galactic nuclei of distant galaxies?
- What do we think is the source of power for active galactic nuclei?
- Do quasars still exist?
- Where do active galactic nuclei fit into the story of galaxy evolution?

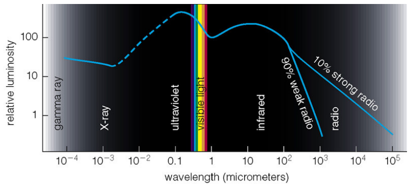
Quasars

- In the early 1960s, Maarten Schmidt identified the radio source 3C 273 with a faint, blue star.
  - the “star’s” spectrum displayed emission lines
  - the wavelengths of these lines matched no known element
- Schmidt realized that the emission lines belonged to Hydrogen, but they were highly redshifted.
- This object is very (> 10^{10} light years) far away.
  - other such objects were subsequently discovered
  - they were called *quasi-stellar radio sources* or **quasars** for short
- The farther away we look out in distance, the farther back we look in *time*!
- Quasars exist only in the *early* Universe!
  - LOOKBACK TIME

Quasar Spectra

- Star-like objects which:
  - have spectra that look nothing like a star
    - highly redshifted
  - can be strong radio sources
    - turns out that 90% are **not**
  - emit light at all wavelengths

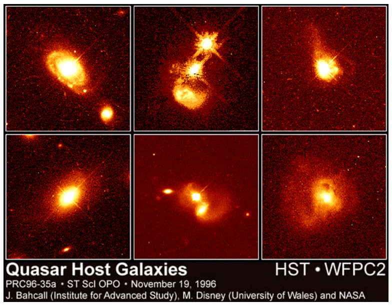




Quasars…

- are extremely luminous.
  - 10^{40} watts
  - 1,000 brighter than the entire Milky Way Galaxy
- are extremely variable.
  - luminosity changes < 1 hour
  - implies they have **a very small size**
- have redshifted emission lines.
  - greatest is 6.8 times the rest wavelength
- have absorption lines at lower redshifts.
  - from gas clouds & galaxies between us and the quasar

Hubble ST shows us that quasars do live in galaxies…they are Active Galactic Nuclei!


Quasar Host Galaxies HST • WFPC2
PRC96-35a • ST ScI OPO • November 19, 1996
J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

Active Galactic Nuclei

- Seyfert Galaxies
  - spiral galaxies with an incredibly bright, star-like center (nucleus)
  - they are very bright in the infrared
  - their spectra show strong **emission** lines


Circinus

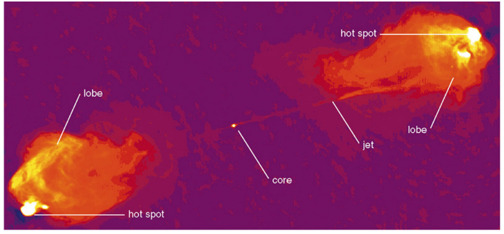
The luminosity can vary by as much as the entire brightness of the Milky Way Galaxy!!

Active Galactic Nuclei

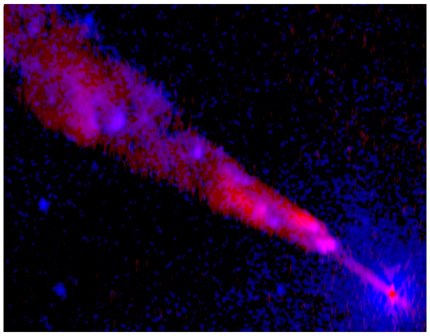
Radio Galaxies

- galaxies which emit large amounts of radio waves
- the radio emission come from *lobes* on either side of the galaxy; **not** the galaxy itself

Cygnus A



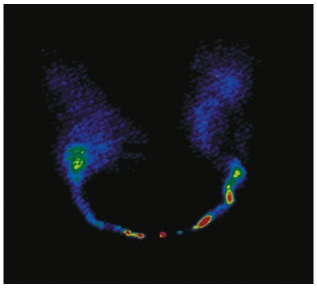
X-ray/Radio Image of Centaurus A



X-ray is blue; radio is red

Radio Galaxy Lobes

These lobes are swept back because the galaxy is moving through an intergalactic medium.

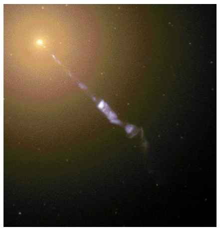


NGC 1265

Active Galactic Nuclei

Jets of matter are shooting out from these galaxies and emitting radio waves, but the matter is **not** cold!

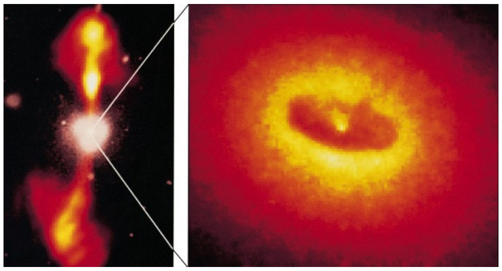
Synchrotron emission --- non-thermal process where light is emitted by charged particles moving close to the speed of light around magnetic fields.



M 87

What powers these Active Galactic Nuclei?

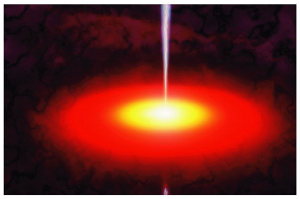
Hubble Space Telescope gave us a clue



NGC 4261

Active Galactic Nuclei

- The energy is generated from matter falling onto a **supermassive black hole**…
  - 1.2 x 10^9 $M_\odot$ for NGC 4261
  - 3 x 10^9 $M_\odot$ for M87
- …which is at the center (nucleus) of the galaxy.



Matter swirls through an accretion disk before crossing over the event horizon.

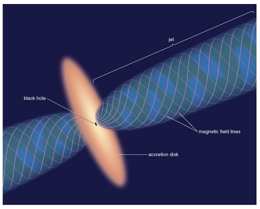
Gravitational pot. energy lost

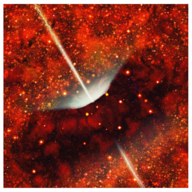
- = mc^2 the mass energy
- 10 – 40% of this is radiated away

Process is very efficient for generating energy.

Active Galactic Nuclei

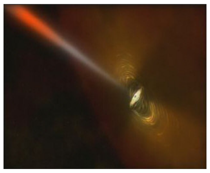
- Formation of the Jets
  - magnetic fields in accretion disks are twisted
  - they pull charged particles out of the disk and accelerate them like a slingshot
  - particles bound to magnetic field; focused in a beam





- Orientation of beam determines what we see:
  - if beams points at us, we see a quasar
  - if not, the molecular clouds/dust of the galaxy block our view of the nucleus
  - so we see a radio galaxy
  - lobes are where jets impact intergalactic medium

Active Galactic Nucleus Animation



Movie. Click to launch.

- Quasars are observed in the distant past (high redshift).
  - this implies that many galaxies had bright nuclei early in their histories, but those nuclei have since gone dormant
- So many galaxies which look "normal" today have supermassive black holes at their centers.
  - such as *Andromeda* and Milky Way?

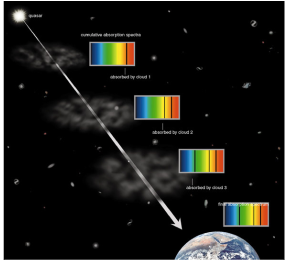
21.6 Shedding Light on Protogalactic Clouds

Our goals for learning:

- How do quasars let us study gas between the galaxies?

A "Forest" of Absorption Lines

- As light from a quasar travels toward Earth…
  - it passes through intergalactic Hydrogen clouds and galaxies
  - each cloud leaves absorption lines at a *different* redshift on quasar spectrum
  - this is the only way we can "observe" protogalactic clouds



- Analysis so far has shown:
  - H lines at high redshift are broader than those at low
  - implies that the gas content of clouds/galaxies is higher in the early Universe
  - more heavy element lines are seen at low redshift
  - supports element enrichment of galaxies by supernovae
- These data support our models of galaxy evolution

What have we learned?

- What do we mean by galaxy evolution and how do we study it?
  - Galaxy evolution is the study of how galaxies form and change with time. We can take advantage of the fact that we are looking further back into time as we look deeper into space. Therefore, even though we cannot witness a single galaxy changing with time, we can create "family albums" showing galaxies as they appeared at different times in the history of the universe.

What have we learned?

- What two starting assumptions do we make in most models of galaxy formation?
  - (1) Hydrogen and helium gas filled all of space when the universe was young. (2) The distribution of matter in the universe was nearly but not quite uniform, so that some regions of the universe were slightly denser than others.

What have we learned?

- Describe in general terms how galaxies are thought to have formed.
  - Gravity slowed the expansion of matter in regions of the universe where the density was slightly greater than average. Within about a billion years after the birth of the universe, gravity had stopped the expansion of these regions and had begun to pull matter together into protogalactic clouds. Halo stars began to form as the protogalactic cloud collapsed into a young galaxy. In galaxies that had enough remaining gas after this initial star formation, conservation of angular momentum ensured that the gas flattened into a spinning disk.

What have we learned?

- What does careful study of our Milky Way Galaxy tell us about galaxy formation?
  - The Milky Way's halo stars are very old and their orbits have random orientations, suggesting that they did indeed form before the protogalactic cloud collapsed into a disk. The low abundances of heavy elements in halo stars tell us they were born before the star-gas-star cycle significantly enriched the interstellar medium with heavy elements. However, the relationship between heavy element abundance and distance from the galactic center suggests that our Milky Way formed not from a single protogalactic cloud but rather from the merger of several smaller protogalactic clouds.

What have we learned?

- How might a galaxy's birth properties have determined whether it ended up spiral or elliptical?
  - There are two basic ways in which birth conditions could have determined whether a galaxy ended up as a spiral galaxy with a gaseous disk or as an elliptical galaxy without a disk. (1) Angular momentum tends to shape a collapsing gas cloud into a spinning disk. Thus, ellipticals may have formed from protogalactic clouds with relatively small amounts of angular momentum, while the clouds that formed spirals had greater angular momentum. (2) Dense clouds tend to cool and form stars more rapidly. Thus, ellipticals may have formed from protogalactic clouds that started out with greater density, leading to a high rate of halo star formation that left little or no gas to collapse into a disk. Spirals may have started form lower-density protogalactic clouds in which a lower rate of halo star formation left enough gas to form a disk.

What have we learned?

- How might interactions between galaxies cause spiral galaxies to become elliptical?
  - Computer models show that two colliding spiral galaxies can merge to form a single elliptical galaxy. The collision randomizes the orbits of the stars, while their combined gas sinks to the center and is quickly used up in a burst of rapid star formation. Spirals may also turn into ellipticals when their gas disks are stripped out by interactions with other galaxies.

What have we learned?

- What do observations of galaxy clusters tell us about the role of galaxy interactions?
  - Observations of clusters of galaxies support the idea that at least some galaxies are shaped by collisions. Elliptical galaxies are more common in the centers of clusters — where collisions also are more common — suggesting that they may have formed from collisions of spiral galaxies. The central dominant galaxies found in cluster centers also appear to be the result of collisions, both because of their large size and the fact that they sometimes contain multiple clumps of stars that probably were once the centers of individual galaxies.

What have we learned?

- What is a starburst galaxy?
  - A starburst galaxy is a galaxy that is forming new stars at a very high rate — sometimes more than 100 times the star formation rate of the Milky Way. This high rate of star formation leads to supernova-driven galactic winds.
- How do we know that a starburst must be only a temporary phase in a galaxy's life?
  - The rate of star formation is so high that the galaxy would use up all its interstellar gas in just a few hundred million years – far shorter than the age of the universe.

What have we learned?

- What can cause starbursts?
  - Many starbursts apparently result from collisions between galaxies. The collision compresses the gas and leads to the high rate of star formation. Some starbursts may occur as a result of close encounters with other galaxies rather than direct collisions. The starburst underway in the nearby Large Magellanic Cloud may have resulted from the tidal influence of the Milky Way.
- What are active galactic nuclei and quasars?
  - Active galactic nuclei are the unusually bright centers found in some galaxies. The brightest active galactic nuclei are called quasars. Active galactic nuclei (including quasars) generally radiate energy across much of the electromagnetic spectrum. In some cases, we see spectacular jets of material shooting out of these objects, sometimes forming huge lobes (revealed by radio observations) at great distances from the center of the galaxy.

What have we learned?

- The nature of quasars was once hotly debated. What evidence supports the idea that they are the active galactic nuclei of distant galaxies?
  - The debate centered on the question of whether quasar redshifts really indicated the great distances that we calculate for them with Hubble's law. The key evidence showing that these distances are correct comes from the fact that we see quasars located in the centers of galaxies in distant clusters — and the redshifts of the quasars, the surrounding galactic material, and the neighboring galaxies in the clusters all match. In addition, the fact that quasars are quite similar to other active galactic nuclei supports the idea that they are simply unusually bright members of this class of object.

What have we learned?

- What do we think is the source of power for active galactic nuclei?
  - We suspect that active galactic nuclei are powered by supermassive black holes that can exceed one billion solar masses. Observations of the rapid variability of active galactic nuclei tells us that their energy output comes from quite a small region, while Doppler shifts of orbiting gas clouds tell us that the central region contains an enormous amount of mass. The only known way that so much mass could be concentrated in such a small region is if it contains a black hole. As matter falls into one of these supermassive black holes, it releases tremendous amounts of energy. This is the only mechanism we know of that can account for the prodigious energy output of active galactic nuclei.

What have we learned?

- Do quasars still exist?
  - Most quasars are found at very large distances, meaning that we are seeing them at a time when the universe was much younger than it is today. Very few quasars are found nearby, although we do find some nearby active galactic nuclei that are less bright than quasars. These observations suggest that quasars are essentially a phenomenon of the past, and that active galactic nuclei may in most cases occur as part of the galaxy formation process.
- Where do active galactic nuclei fit into the story of galaxy evolution?
  - Because quasars were much more common in the past, it is likely that many galaxies once had very bright nuclei that have now gone dormant. If so, then many galaxies that now look quite normal have supermassive black holes at their centers.

What have we learned?

- How do quasars let us study gas between the galaxies?
  - Quasars are bright enough to be easily detected at distances most of the way to the cosmological horizon. Each cloud of gas through which the quasar's light passes on its long journey to Earth leaves a fingerprint in the quasar's spectrum. We can distinguish the different clouds of gas because each one produces hydrogen absorption lines with a different redshift in the quasar spectrum. Study of these absorption lines in quasar spectra allows us to study gas — including protogalactic clouds — that we cannot otherwise detect.

Why should we not be surprised that galaxy collisions were rather common in the past?

1. Galaxies moved faster in the past and therefore collided more often.
2. Galaxies were larger in the past and therefore collided more often.
3. Both (1) and (2).
4. The universe was much denser in the past, so its galaxies were much closer together, making collisions much more frequent.
5. Because elliptical galaxies are formed by the collision of two spiral galaxies, ellipticals are observed to be more common in the past.

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Why do dwarf galaxies that have undergone bursts of star formation tend to have fewer heavy elements than large galaxies?

1. Because dwarf galaxies only contain low mass stars which don’t form heavy elements.
2. Because heavy elements only form in massive galaxies.
3. Star bursts in dwarf galaxies can eject heavy elements so they have fewer of these to incorporate into new stars.
4. Star bursts in dwarf galaxies do no last long enough to build up a high proportion of heavy elements.

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2. Because heavy elements only form in massive galaxies.
3. **Star bursts in dwarf galaxies can eject heavy elements so they have fewer of these to incorporate into new stars.**
4. Star bursts in dwarf galaxies do no last long enough to build up a high proportion of heavy elements.

Heavy elements ought to be much more common near the Milky Way’s center than at its outskirts.

1. Yes, heavy elements sink toward the center so we would expect to find a higher proportion of them there.
2. Yes, stars create heavy elements and there has been much more star formation near the Milky Way’s center than at its outskirts.
3. No, the migration of stars around the galaxy spreads the heavy elements out evenly across the Milky Way.
4. No, galaxy collisions have resulted in a random distribution of heavy element proportions across the Milky Way.

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Starburst galaxies have been forming stars at the same furious pace since the universe was about a billion years old.

1. Yes, starburst galaxies are the most prolific regions of star formation in the universe.
2. No, after too many stars form, a black hole results and a galaxy stops forming stars.
3. No, the bursts of star formation would use up all the gas in a galaxy in a much shorter period of time than the age of the universe.
4. No, starburst galaxies are only found in the nearby universe, and are all very young.

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1. Yes, active nuclei in other galaxies appear to be powered by accretion into similar sized black holes.
2. Yes, the Milky Way has a very similar appearance to other galaxies with active nuclei.
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