Part X
The Evolution of Galaxies

Chemical Evolution

Overview of Chemical Evolution

- After the Big Bang the Universe consisted of mainly hydrogen and helium.
- The first generation of stars started the process of stellar nucleosynthesis, which continued with subsequent generations of stars, resulting in rising abundances of heavier elements.
- This enrichment occurs while the stars are "normal" stars, but also in processes at the end of stellar lives (e.g. supernovae).
- Some enriched material will be tied up in stellar remnants (neutron stars, black holes and white dwarfs) and effectively lost to future star-formation.
- Stars can disperse this "enriched" material via stellar winds and by supernova explosions.
- The lifetimes of massive stars are very short compared to galactic timescales (i.e. a few Myr for the most massive stars).
- The lifetimes of low mass stars are longer than the current age of the Universe – meaning that the heavy elements in these stars are effectively locked up as well.
- Galaxy internal motions (i.e. rotation) and interactions (galactic cannibalism/ mergers etc) can further distribute this enriched material.
- Galaxies may suffer outflows (for example, in starburst events) and also inflow of less chemically enriched material.
- For galaxies with shallower potential wells – outflows can occur more easily
- This process occurs in the context of galaxies. Galaxies are complex entities, with a range of sizes. The chemical enrichment may be localised.
- There exist metallicity gradients in galaxies (see Fig. 10.1).
- Type I supernovae – explosion of a white dwarf in a binary system – SN ejecta rich in Fe.
- Type II supernovae – explosion of massive star ($> 10M_{\odot}$) – SN ejecta rich in O, Mg etc.
- O/Fe ratio – indicator of relative ratios of Type II /Type I supernovae.

The Closed Box Model of Galactic Chemical Evolution

Consider a galaxy as an isolated and closed box.
The galaxy starts with a low metallicity.
Stars are born and die and recycle nuclear processed material to the ISM, out of which another generation of stars are born.
Subsequent generations of stars gradually results in a build-up of heavier elements, both in stars and in the interstellar medium.

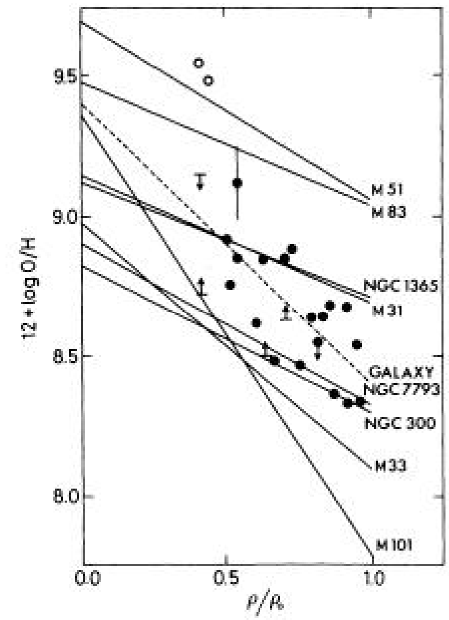

Figure 10.1: The metallicity gradients in nearby galaxies. The x-axis is the galactocentric radius (normalised to the de Vaucouleurs radius). The y-axis is the metallicity (as measured by the oxygen abundance compared to the hydrogen abundance). The sloping lines show that the inner regions of galaxies have higher metallicities than the outer regions (image taken from Shaver et al. 1983).

Assumptions

- Assume that the galaxy is well mixed – same composition everywhere.
- Instantaneous recycling – nuclear processed material is returned to the ISM much faster than the time taken to form a significant fraction of stars.
- No inflow or outflow of material.

This is the *1-zone, instantaneous recycling, closed box model.*

Definitions

$M_s(t)$: the mass of low mass stars in the galaxy at a time t.

$M_h(t)$: the total mass of heavier elements (elements heavier than helium) in the galaxy ISM at a time t.

$M_g(t)$: the total mass of gas in the galaxy at a time t.

$Z(t)$: The metallicity of the gas at a time t.

$$Z(t) = \frac{M_h(t)}{M_g(t)} \tag{10.1}$$

The yield p, defined as the fraction of heavy elements returned to the ISM.

Form a mass $\Delta' M_s$ of stars $\rightarrow \Delta M_s$ of low-mass stars
$\rightarrow p\Delta M_s$ of heavier elements returned to ISM

Value of yield p depends on several things, particularly the initial mass-function (IMF) of stars (i.e. fraction of massive stars)

Analysis

At a time t a mass $\Delta' M_s$ of stars are formed and subsequently evolve.
Of this mass, some will be tied up in low mass stars and some will result in the formation of high mass stars and subsequent enrichment of the gas in the galaxy.

$$\Delta M_h = p\Delta M_s - Z\Delta M_s = (p - Z)\,\Delta M_s \tag{10.2}$$

$$\Delta Z = \Delta\left(\frac{M_h}{M_g}\right) = \frac{M_g \Delta M_h - M_h \Delta M_g}{M_g^2} \tag{10.3}$$

or

$$\Delta Z = \frac{p\Delta M_s - Z\left[\Delta M_s + \Delta M_g\right]}{M_g} \tag{10.4}$$

If the galaxy is a closed box - nothing enters and nothing leaves, then $\Delta M_s + \Delta M_g = 0$ and so

$$\Delta Z = \frac{p\Delta M_s}{M_g} = -\frac{p\Delta M_g}{M_g} \tag{10.5}$$

which can be integrated up to give the time evolution of the galaxy metallicity:

$$Z(t) = Z(0) + p\ln\left[\frac{M_g(0)}{M_g(t)}\right] \tag{10.6}$$

Metallicity grows as stars are formed and gas is used up.

The Local Yield p

The Sun is more metal rich than the local ISM.
In the solar neighbourhood $Z(\text{now}) = 0.7 Z_\odot$.

Near the Sun, the Milky Way disk contains: $30 - 40 M_\odot$ pc^{-2} in stars
$13 M_\odot$ pc^{-2} in gas
$\sim 50 M_\odot$ pc^{-2} in total

This means that

$$Z(\text{now}) \sim 0.7 Z_\odot \sim p\log_e(50/13) \quad \text{or} \quad p \sim 0.5 Z_\odot \tag{10.7}$$

Note that $Z_\odot$ is equivalent to $Z = 0.02$.

Metallicity of Stars in Solar Neighbourhood

Consider the mass of stars formed before a time t.
These stars will have a metallicity less than $Z(t)$.
This mass of these stars will be just $M_s(< Z) = M_g(0) - M_g(t)$.
From earlier equation (10.6), we have:

$$M_s(< Z) = M_g(0) \left[1 - \exp\left(- \left[Z(t) - Z(0)\right]/p\right)\right] \tag{10.8}$$

Consider the metallicity of stars local to the Sun, and assume $Z(0) = 0$.
We would expect a substantial fraction of low-metallicity stars.

$$\frac{M_s(< 0.25 Z_\odot)}{M_s(< 0.7 Z_\odot)} = \frac{1 - \exp\left[-0.25 Z_\odot/p\right]}{1 - \exp\left[-0.7 Z_\odot/p\right]} \sim 0.5 \tag{10.9}$$

Closed box model suggests 1/2 of all stars near the Sun should have $Z < 0.25 Z_\odot$.
Observationally only 2% of F+G stars have $Z < 0.25 Z_\odot$.
This is termed the **G dwarf problem**.
Possible Solution: Pre-enrichment from the bulge to the disk. Starting metallicity of $Z(0) = 0.25 Z_\odot$.

Modifications to the Closed Box Model: Leaky Box Model

Consider a galaxy that is not a closed box, but loses mass as part of the star-formation process.
Define M_T as the total mass of stars and gas in the galaxy.
Assume that some material leaks out of the galaxy, and that the amount of material lost is proportional to the amount of stars that are formed.
This leads to

$$\Delta M_T = -c \Delta M_s \tag{10.10}$$

Assume that:
$Z(0) = 0$ – ie zero initial metallicity, and
$M_s(0) = 0$ – no stars at beginning.

Then we can integrate to find that

$$M_T(t) = M_T(0) - c M_s(t) \tag{10.11}$$

And now, by definition, $M_T(t) = M_g(t) + M_s(t)$
We have that

$$M_g(t) = M_T(0) - (1 + c) M_s(t) \tag{10.12}$$

We can repeat the earlier analysis to find (assuming gas expelled has same metallicity as the ISM):

$$\Delta Z = \frac{p \Delta M_s}{M_g} = \frac{p \Delta M_s}{M_T(0) - (1 + c) M_s} \tag{10.13}$$

which integrates to

$$M_s(< Z) = \frac{M_T(0)}{1+c}\left[1 - \exp\left[-\frac{(1+c)Z}{p}\right]\right] \tag{10.14}$$

Consequences of Leaky Box model:

The outflow of gas reduces the yield by a factor $1/(1+c)$ to $p/(1+c)$ – the **effective yield**.
For galaxies, models suggest that $c \propto \sigma_*^{-1}$, where σ_* is the stellar velocity dispersion.
For giant elliptical galaxies (with $\sigma_* \geq 300 - 400$ km s^{-1}), $c < 1$.
For dwarf galaxies (with $\sigma_* < 100$ km s^{-1}), $c \sim$a few.
Decent agreement with mass-metallicity relationship for galaxies.

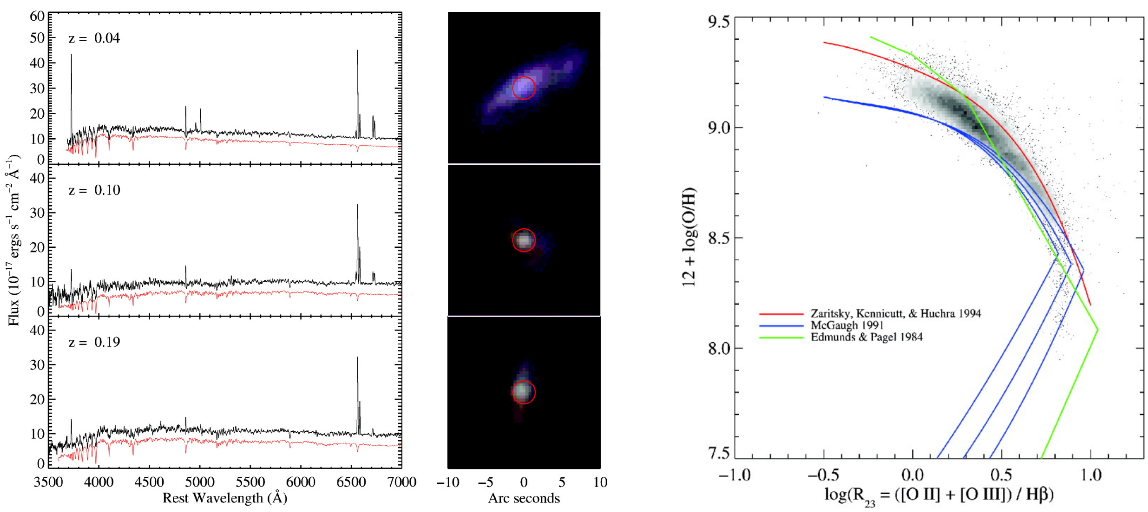

Figure 10.2: Left panel: Examples of spectra and images of star-forming galaxies from the SDSS survey, along with images of the galaxies. Note the emission lines. Most prominent are Hβ (4862Å), OII (3727Å), OIII (4959Å+5007Å) and Hα (6563Å). Right panel: the relationship between the ratio R_{23} and the metallicity, expressed as $12+\log_{10}$ O/H. Note potential ambiguity. These images are taken from Tremonti et al. (2004).

Comparison with Observations

The metallicity of gas in a galaxy is often referred to in terms of the oxygen to hydrogen abundance.
Oxygen has been adopted as the canonical "metal" for ISM studies because:

1. it is the most abundant,
2. it is only weakly depleted onto dust grains (i.e. mostly stays in a visible state),
3. it displays strong lines in the optical.

We use the term metallicity to denote the gas-phase oxygen abundance, measured in units of $12 + \log_{10}(\mathrm{O/H})$, where the ratio O/H is the abundance (by number) of oxygen relative to hydrogen.

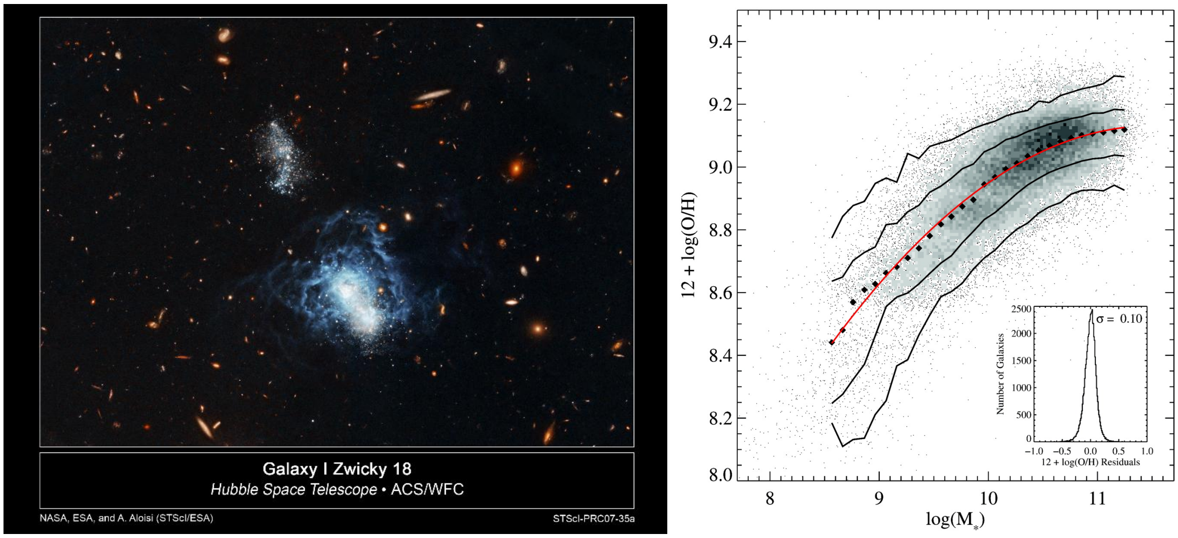

Figure 10.3: Left: the low metallicity galaxy I Zw 18. While the stars in the galaxy have extremely low metallicity it is not a young galaxy, as it contains old stars. The galaxy is also strongly star-forming (blue wisps indicative of an outflow). It also has a nearby companion galaxy. Right: The mass-metallicity relationship for 53,000 star-forming galaxies, with data from the Sloan Digital Sky Survey (SDSS). The x-axis is the mass of the stars in the galaxy, and the y-axis is a measure of the oxygen metallicity with respect to hydrogen. The data are the (many) points, and the solid lines show the best fit (Tremonti et al. 2004).

Ratio determined from emission lines ratios, using OII 3727Å and OIII 4959Å, 5007Å lines, with respect to Hβ line (4862Å).

Define a ratio R_{23} in terms of the equivalent widths of emission lines:

$$R_{23} = \frac{\text{OII }(3727\text{Å}) + \text{OIII }(4959 + 5007\text{Å})}{H\beta} \tag{10.15}$$

The metallicity is related directly to the value of R_{23} (see Figure 10.2).

Usually plotted as $12 + \log_{10}(\text{O/H})$ and for most galaxies this values lie in range $8.0 - 9.5$.

Solar metallicity ($Z_\odot$) in these units is 8.69.

Lowest known metallicity galaxy, I Zwicky 18, with $(\text{O/H}) \sim 0.02(\text{O/H})_\odot$, or $12 + \log_{10}(\text{O/H}) = 7.0$.

Inflow Model

Similar to "Leaky Box" model, except with inflow of material rather than outflow.

Imagine a galaxy that is forming stars undergoes occasional inflow of low metallicity material.

This will tend to result in a large scatter in a metallicity *versus* age diagram for stars - which is seen (below).

If lower mass galaxies suffered relatively higher levels of inflow this could also explain the mass-metallicity relationship that is observed for galaxies.

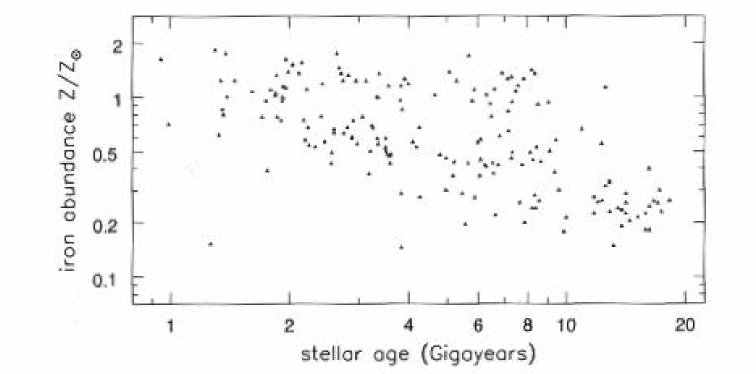

Figure 10.4: The scatter in Fe abundance with age for a sample of nearby F stars. Younger stars (i.e. more recently formed) tend to be richer in iron, but there is a large scatter (Edvardsson 1993).

However, this is not believed to be the case, and outflows are the preferred mechanism.

The Dynamical Evolution of Galaxies

Passive Evolution

Consider an isolated galaxy, that does not suffer from mergers/infall and has no substantial star-formation (and hence no substantial ISM).

The stellar population will simply age – young massive stars will evolve and explode as SN, older stars will evolve away from the main sequence, and become giants etc.

Observationally, the galaxy will simply redden.

No galaxies are "simple" like this (at least over the age of the Universe).

More Complete Picture

Several different forces are at work in real galaxies:

- Passive evolution of the stellar population.
- Galaxy mergers, including capture of smaller dwarf galaxies. Starburst can result and the process can result in spirals being turned into ellipticals.

  Preferentially happens in denser environments (groups rather than clusters though) due to "dynamical friction".
- Outflows from galaxies in starbursts. Can stop future star-formation in dwarf galaxies, by removing all of the ISM.

- Galaxy "harassment" in groups and clusters. Frequent weak encounters in a cluster. Results – induced bars – disturbed morphology – starbursts – simulations suggest the process can result in a final elliptical morphology – galaxy transformation.

  At $z = 0.4$ –lots of disturbed spirals in clusters – local clusters dominated by ellipticals.

- Ram-pressure stripping of galaxy ISM in clusters. Can strip the ISM from a spiral galaxy and the result may be an S0 galaxy. NGC 4402 is an example of this process in action (Fig. **??**).

- Galaxy strangulation – tidal effects can also gradually strip gas out of a galaxy – no gas – no ongoing star-formation. Spiral galaxy will become a red spiral (spirals arms but no star-formation) and eventually (probably) an S0.

Dynamical Friction

Most galaxies are in groups or clusters and they will interact with their neighbours – "fly-bys" up to galaxy mergers.

Why do galaxies merge?

Consider a galaxy of mass M, with a velocity V, passing by an individual star, of mass m, in another galaxy (we will consider all the stars in due course).

The distance between the star and the path of the galaxy is b.

Assume core size of the galaxy is small – that is $r_c \ll b$.

$t = 0$: time of closest approach – distance of the galaxy from this point: Vt.

Assume force is small and that the deviation of motion of galaxy is small.

The perpendicular force on the galaxy, $F_\perp$, will be

$$F_\perp = \frac{GMm}{r^2}\frac{b}{r} = \frac{GMmb}{(b^2 + V^2t^2)^{3/2}} = M\frac{dV_\perp}{dt} \tag{10.16}$$

where $r^2 = b^2 + V^2t^2$ and $V_\perp$ is the perpendicular velocity of the galaxy.

To get the resulting perpendicular velocity we need to integrate, so

$$\Delta V_\perp = \frac{1}{M}\int_{-\infty}^{+\infty} F_\perp dt = \int_{-\infty}^{+\infty} \frac{Gmb}{(b^2 + V^2t^2)^{3/2}} dt = \frac{2Gm}{bV} \tag{10.17}$$

Assume that $Vt = b\tan\theta$ (remembering that V and b are assumed to be constant).

So, as the galaxy moves pass the star it acquires a perpendicular velocity $\Delta V_\perp$, with

$$\Delta V_\perp = \frac{2Gm}{bV} \tag{10.18}$$

The star in the galaxy must gain and equal and opposite amount of momentum, so that the total KE in the perpendicular direction is:

$$\Delta KE_\perp = \frac{M}{2}\left(\frac{2Gm}{bV}\right)^2 + \frac{m}{2}\left(\frac{2GM}{bV}\right)^2 = \frac{2G^2mM(M+m)}{b^2V^2} \tag{10.19}$$

The object of smaller mass acquires most of the energy.

This energy must come from the forward motion of the galaxy.

If we assume that the PE a long time before and after the encounter is very small (i.e. zero) we can equate the kinetic energies, so that:

$$\frac{1}{2}MV^2 = \Delta KE_\perp + \frac{M}{2}\left(V + \Delta V_\parallel\right)^2 + \frac{m}{2}\left(\frac{M\Delta V_\parallel}{m}\right)^2 . \tag{10.20}$$

where $\Delta V_\parallel$ is the small change in velocity in the direction of motion of the galaxy.

If we assume that $\Delta V_\parallel \ll V$ and so ignore higher order terms ($\Delta V_\parallel^2$), then we have

$$-\Delta V_\parallel \sim \frac{\Delta KE_\perp}{MV} = \frac{2G^2 m(M+m)}{b^2V^3} \tag{10.21}$$

Image now our galaxy (mass M) passes through a region of the 2nd galaxy with a density of n stars of mass m per cubic parsec:

$$-\frac{dV}{dt} = \int_{b_{min}}^{b_{max}} nV \left[\frac{2G^2 m(M+m)}{b^2V^3}\right] 2\pi b db = \frac{4\pi G^2(M+m)}{V^2} nm \ln\Lambda \tag{10.22}$$

where $\Lambda = b_{max}/b_{min}$.

We take b_{min} to be the strong encounter radius (defined earlier) and b_{max} to be distance where the density of stars become very small.

Dynamical Friction – Implications

This galaxy deceleration is referred to as *dynamical friction*, and is important as it means galaxies in a cluster or group will lose KE and can potentially merge.

Slow encounters - small V drains more energy than a high speed encounter ($-dV/dt \propto V^{-2}$).

This often means that the galaxy at the centre of the potential well of the group or cluster will tend to preferentially accrete and grow.

For satellite galaxies – loss of velocity is bigger for more massive galaxies – LMC will merge with Milky Way in a few Gyr, while globular clusters (which are much lighter) will carry on orbiting for longer.

Energy removed from forward motion goes into "puffing" up the disks of the galaxy – galaxy expands.

Suppose before encounter the galaxy has KE_0 and PE_0, then $2KE_0 + PE_0 = 0$ (Virial Theorem).

Total internal energy $E_0 = KE_0 + PE_0 = -KE_0$.

Long after encounter – galaxy in Virial equilibrium, – E_1, KE_1 and PE_1

Dynamical friction increases galaxy internal energy by ΔKE, so that $E_1 = E_0 + \Delta KE$.

Now $KE_1 = -E_1 = -(E_0 + \Delta KE) = KE_0 - \Delta KE$

Stars that gain the most energy can escape from the galaxy – others less closely bound.

- For dynamical friction to be effective lower velocity encounters are better – groups rather than clusters.

- The orientation of the disks can also play a role.

  If one of the disks lies in the plane of the "orbit" between the two galaxies (and also rotates in the same sense) particularly strong effects are seen.

  Disk rotation tends to cancel out relative motion – reducing effective velocity.

- Motion of galaxies is typically too fast in big clusters for mergers – motion of galaxies in clusters increases with cluster mass. Lots of "harassment" instead.
- The actual process of merging is complicated and depends on specific details of the galaxies (size, orientation etc), with the formation of tidal tails, enhanced star-formation and other complexities.
- Movies can be found on Chris Mihos website

  `http://burro.cwru.edu/models/models.html`

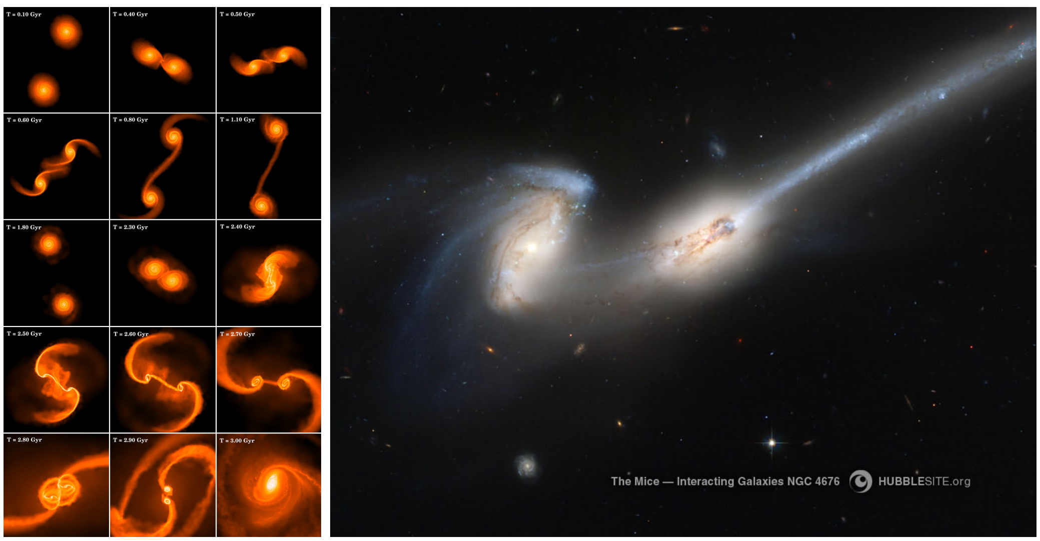

Figure 10.5: Left panel: Simulations of merging galaxies, showing the expected evolution over several Gyr. Right panel: A HST image of the "Mice" merging galaxies (NGC 4676), showing the tidal tails.

Mergers: Wet and Dry

The final outcome of a merger event will also will depend on whether it is a *WET* or *DRY* merger.

Wet Mergers: When both of the galaxies have a substantial ISM (ie both are disk galaxies).

Wet mergers – trigger additional star-formation – fuelling of the central black hole (i.e. trigger quasar activity) and eventually transform disk galaxies into ellipticals.

Dry Mergers: When both galaxies have little ISM (ie both ellipticals).

Less dynamical effect – result is another elliptical, but are important in growth of massive red galaxies (sometimes called GREGs – Giant Red Elliptical Galaxies).

The $M - \sigma$ Relation for Black Holes

There is a strong correlation between the inferred mass of the central black hole in galaxies and the velocity dispersion of the host bulge (entire elliptical galaxy or the bulge of a spiral galaxy).

In turn, the σ of a bulge is directly related to the mass of the bulge.

The best current estimate is

$$\log(M/M_\odot) = 8.12 \pm 0.08 + (4.24 \pm 0.41) \log(\sigma/200 \text{ km s}^{-1}) \tag{10.23}$$

M is the black hole mass and σ the host bulge velocity dispersion (Gultekin et al. 2009).

Expressed another way – the ratio of the black hole mass to the host bulge mass is 1/1000.

The "Radius of Influence" for even a large black hole is much smaller than the galaxy.

How does the black hole know about the rest of the galaxy (and vice versa)?

Implications for black-hole growth and galaxy evolution:

Black holes grow by accreting material from the galaxy – in turn this accretion liberates a lot of radiation (i.e. a quasar) – this radiation ionizes material and further regulates the accretion onto the black hole.

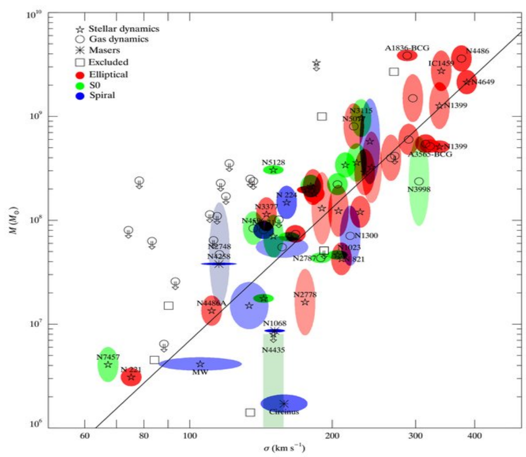

Figure 10.6: The $M - \sigma$ relation for black holes. Data from Gultekin et al. (2009).