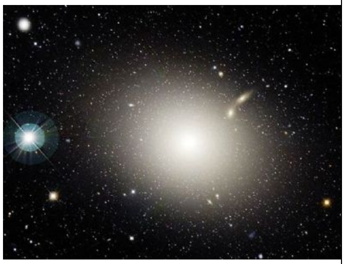
STAR FORMATION IN GALAXIES

Part IX

- The ISM and star formation
- Where do stars form?
- How to measure star formation
- How to kill a galaxy (effect of environment)



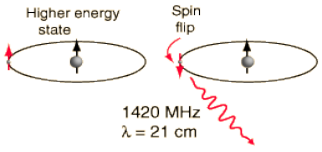
Interstellar Medium (ISM)

- Interstellar space is not empty - there is gas and dust in the galaxy
- Chemical composition of gas is mostly hydrogen (~70%), some metals (~few %) and rest helium.
- Clouds can be mainly
  - Neutral hydrogen (HI)
  - Ionized hydrogen (HII)
  - Molecular hydrogen (H_2)
- **Where do stars form?**

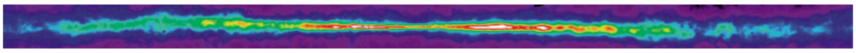
Interstellar Medium (ISM) - HI regions

- Electrons have charge and spin, and so have a magnetic dipole moment.
- Pauli Exclusion Principle:. For a pair of electrons, if their spins are aligned, they have slightly more energy, than if they had opposite spin
- Energy difference is small ~6×10^{-6} *eV*, which is ~21 *cm* (radio waves).

From radio surveys of our galaxy we find lots of HI gas: about 1 solar mass of gas for every 10 solar masses of stars.



Radio



IR

Interstellar Medium (ISM) - HII regions

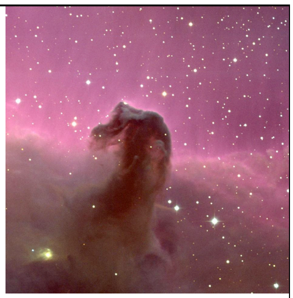
HST: Keyhole nebula

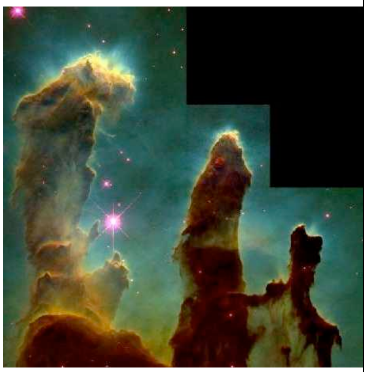
- HII regions are found near hot stars.
- UV photons from nearby stars ionize H atoms.
- When electrons and protons recombine, they generally emit Balmer lines.
- Also observe lines from other atoms (e.g., oxygen, sulphur, silicon, carbon, …).
- HII regions are associated with active star formation.

Interstellar Medium (ISM) - H_2 regions

- If density of gas is high, and temperature is low enough, H atoms can form H_2. Unfortunately, there is no emission from H_2 in the optical or radio bands. Therefore use,
  - Far-infrared- dust emission
  - Other molecules: CO
  - Dust and molecular gas is often found together

o Where there is lots of gas - in particular molecular and ionized gas => lots of stars formation …





Gravitational Collapse in the ISM

- The Jeans Mass

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

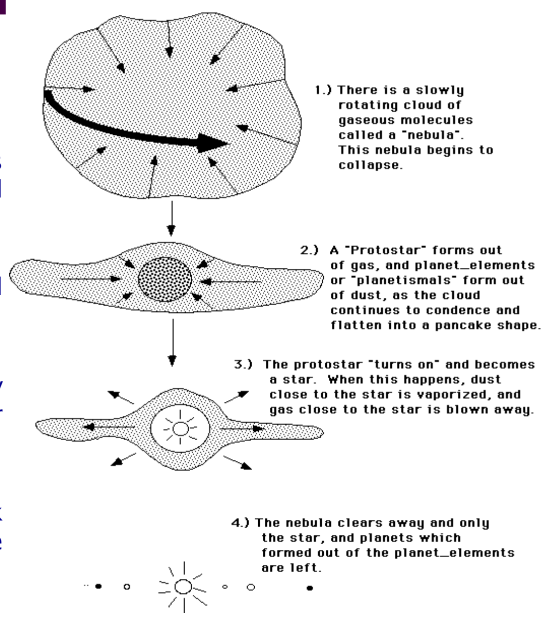
	Diffuse HI Cloud	H_2 Cloud Core
T	50 K	10 K
ρ	$5\times 10^8\ m^{-3}$	$10^{10}\ m^{-3}$
M_J	1500 $M_\odot$	10 $M_\odot$
M_c	1-100 $M_\odot$	10-1000 $M_\odot$

- We know from the ***Jeans Criterion*** that if $M_c>M_J$ collapse occurs.
- Substituting the values from the table into gives:
  - Diffuse HI cloud: $M_J \sim 1500\ M_{Sun}$ => stable as $M_c<M_J$.
  - Molecular cloud core: $M_J \sim 10\ M_{sun}$ => unstable as $M_c>M_J$.

- So deep inside molecular clouds the cores are collapsing to form stars.

Cloud Collapse and Star/Planet Formation

- Jeans cloud collapse equations describe the conditions required for an ISM cloud to collapse.
- As a cloud collapses, central temperature increases.
- This is accompanied by spinning-up of the central star (to conserve AM).
- If the cloud is rotating, the disk also flattens into an oblate spheroid.



Time-scale for collapse

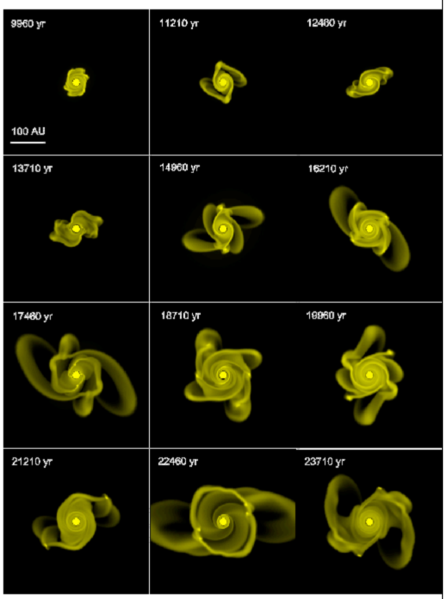
- The collapse time-scale t_{ff} when $M > M_J$ is given by the time a mass element at the cloud surface needs to reach the centre.
- In free-fall, an mass element is subject to acceleration $g = \frac{GM}{R^2}$
- By approximating R using $R^3 \sim M/\rho \Rightarrow t_{ff} \approx (G\rho)^{-1/2}$
- Higher density at cloud centre = > faster collapse.
- For typical molecular cloud, $t_{ff} \sim 10^3$ years (ie very short).

Nebular Collapse

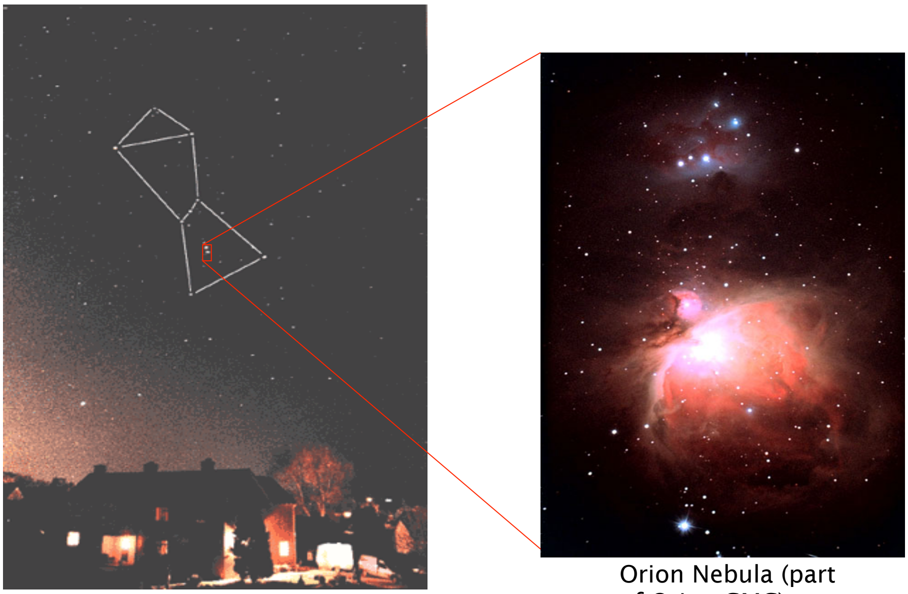
- The Solar system was formed from a giant molecular cloud, known as a *primordial nebula.*
  - Similar to the Orion Nebula (right).
- This nebula may have only contained only 10-20% more mass than the present solar system.
- Due to some disturbance, perhaps a nearby supernova, the gas was perturbed, causing ripples of increased density
- The denser material began to collapse under its own gravity…

Proto-star and Disk Formation

- The original nebula must have possessed some angular momentum. Due to the spin, the cloud collapsed faster along the 'poles' than the equator.
- The result is that the cloud collapsed into a spinning disk.
- Disk material cannot easily fall all the remaining way into the centre because of its rotational motion, unless it can somehow lose some energy, e.g. by friction in the disk (collisions).
- The initial collapse takes just a few 100,000 years.



Orion GMC



Orion Nebula (part of Orion GMC)

Problem of star formation efficiency

Gas in the galaxy should be wildly gravitationally unstable. It should convert all its mass into stars on a free-fall time scale:

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}} = \frac{3.4\times10^{10}}{\sqrt{n}}\ \rm yr$$

For interstellar medium (ISM) in our galaxy: $n \approx 2\times10^{5}\ \rm m^{-3}$

$$t_{\rm ff} = 8\times10^{6}\ \rm yr$$

Total amount of molecular gas in the Galaxy: $\sim 2\times10^{9} M_{\rm sun}$

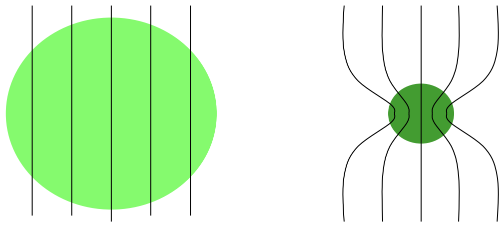
Expected star formation rate: $\boxed{\sim 250\ M_{\rm sun}/\rm year}$

Observed star formation rate: $\boxed{\sim 3\ M_{\rm sun}/\rm year}$

Something slows star formation down…

Magnetic field support

In presence of B-field, the stability analysis changes. Magnetic fields can provide support against gravity.



Replace Jeans mass with critical mass, defined as:

$$M_{cr} = 0.12 \frac{\Phi_M}{G^{1/2}} \approx 10^3 M_{sun} \left(\frac{|\mathbf{B}|}{3\,\mathrm{nT}} \right) \left(\frac{R}{2\,\mathrm{pc}} \right)^2$$

nT is nano-Tesla!

Magnetic field support

Consider an initially stable cloud. We now compress it. The density thereby increases, but the mass of the cloud stays constant.

Jeans mass *decreases:*

$$M_J \propto \frac{1}{\sqrt{\rho}}$$

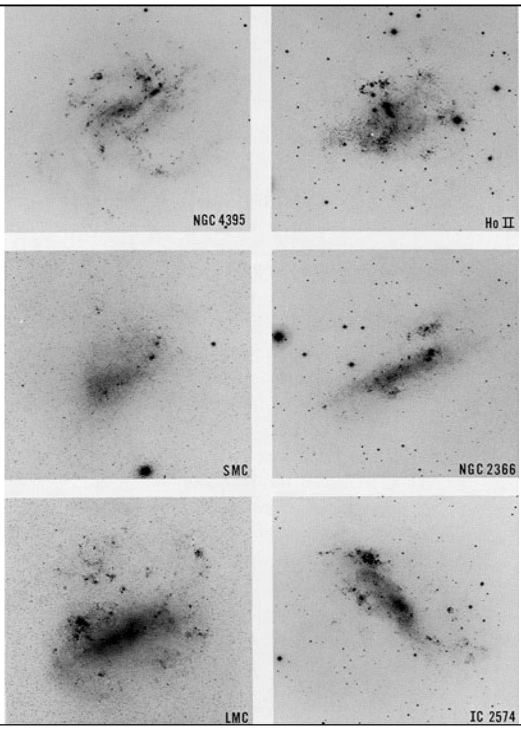
If no magnetic fields: there will come a time when $M>M_J$ and the cloud will collapse.

But M_{cr} stays constant (the magnetic flux will be frozen in the cloud)

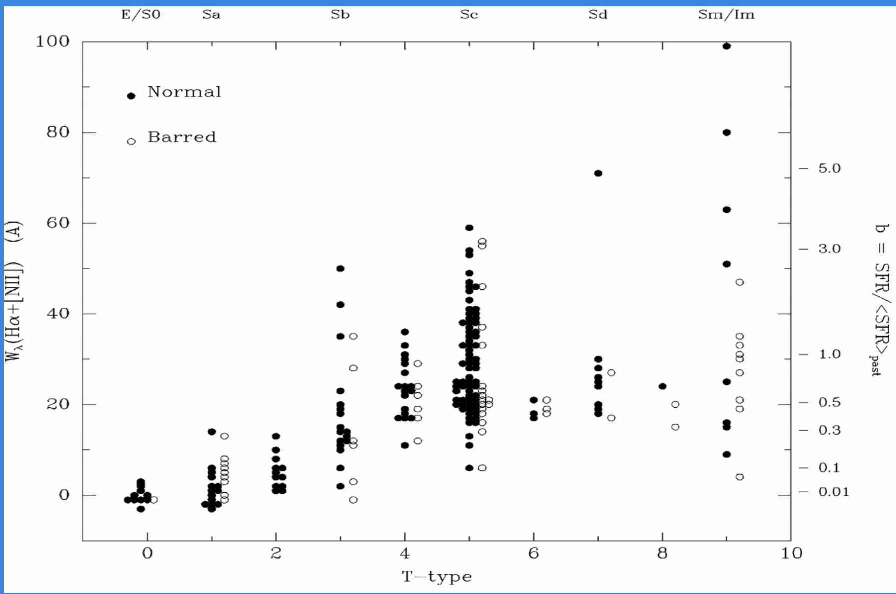
So if B-field is strong enough to support a cloud, no compression will cause it to collapse.

Where is the star formation?

Star formation regions are obvious in these Sm-Irr galaxies



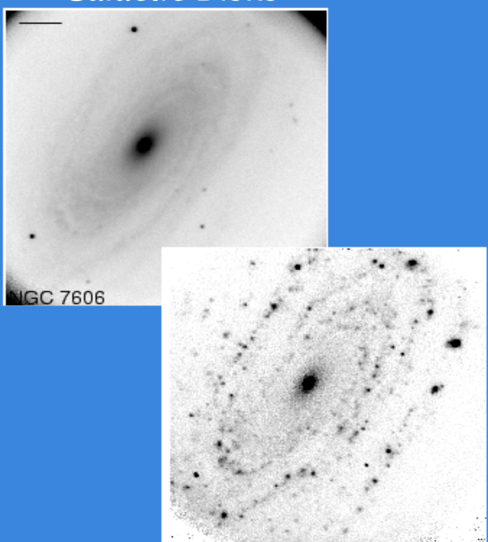
Where - General



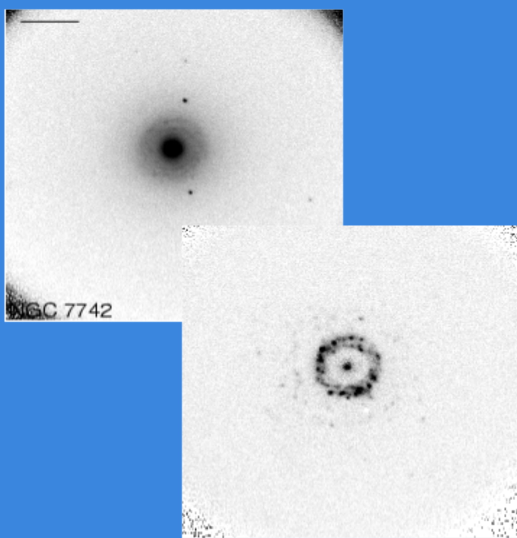
SF Trend Along Hubble Sequence

Where - Global

Galactic Disks



(Circum)nuclear



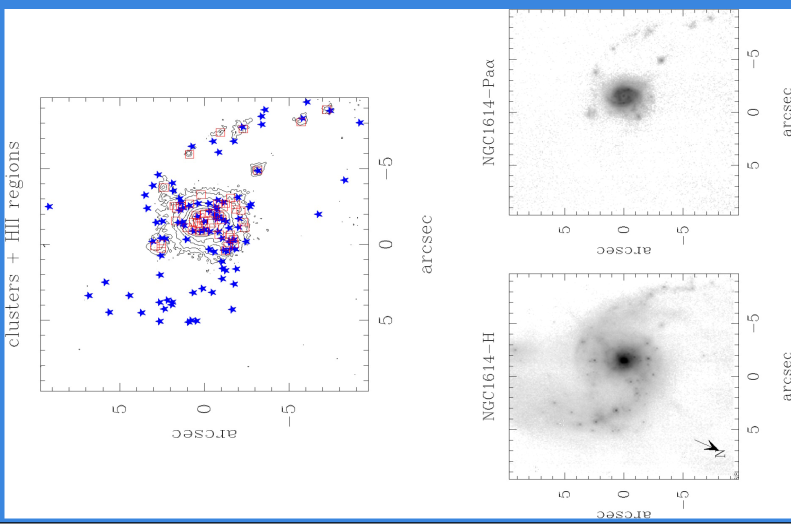
Where - Global Properties

Table 1. Star formation in disks and nuclei of galaxies

Property	Spiral disks	Circumnuclear regions
Radius	1-30 kpc	0.2-2 kpc
Star formation rate (SFR)	0-20 $M_\odot$ year^{-1}	0-1000 $M_\odot$ year^{-1}
Bolometric luminosity	10^6-10^{11} $L_\odot$	10^6-10^{13} $L_\odot$
Gas mass	10^8-10^{11} $M_\odot$	10^6-10^{11} $M_\odot$
Star formation time scale	1-50 Gyr	0.1-1 Gyr
Gas density	1-100 $M_\odot$ pc^{-2}	10^2-10^5 $M_\odot$ pc^{-2}
Optical depth (0.5 µm)	0-2	1-1000
SFR density	0-0.1 $M_\odot$ year^{-1} kpc^{-2}	1-1000 $M_\odot$ year^{-1} kpc^{-2}
Dominant mode	steady state	steady state + burst
Type dependence?	strong	weak/none
Bar dependence?	weak/none	strong
Spiral structure dependence?	weak/none	weak/none
Interactions dependence?	moderate	strong
Cluster dependence?	moderate/weak	?
Redshift dependence?	strong	?

Where - Local

- HII Regions

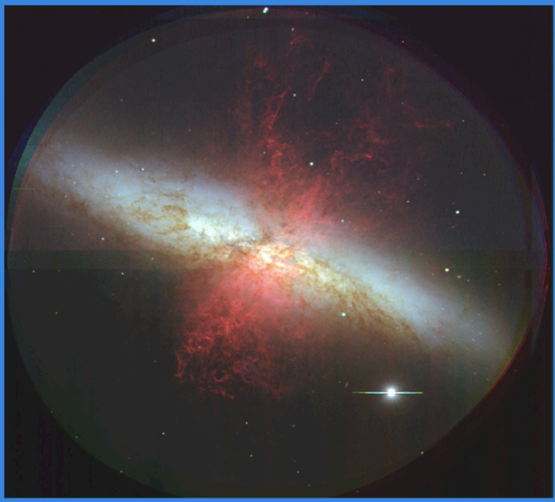


Where - Special Cases

Starburst

- Short-Lived
- Intense
- Circumnuclear
  (kpc Scale)

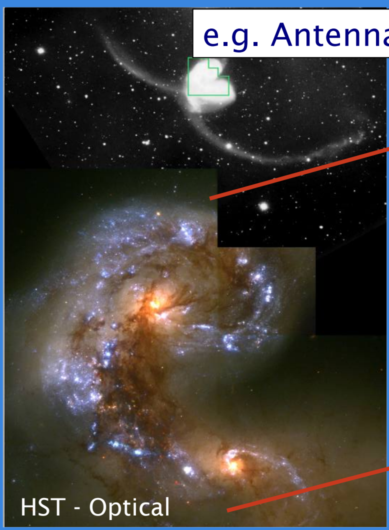
- Can dominate the bolometric luminosity
- Often dust obscured
- Drives hot outflows

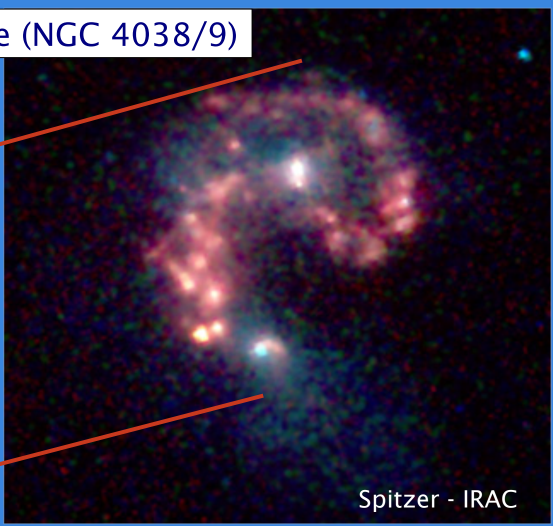


Where - Special Cases

ULIRG (Ultraluminous IR Galaxy) - Merger - Dust heated by SF and/or AGN

e.g. Antennae (NGC 4038/9)





How to Measure Star formation

Calculating star formation rate

- There is an enormous (10^7) **range** in galaxy star formation rates : 10^{-4} - 10^3 $M_\odot$ yr^{-1}
  Loosely, we divide this range into two regimes :
  (i) **normal galaxies** (≈75% of local SF) have SFRs : 0 - few $M_\odot$ yr^{-1}
  note: integrated galaxy spectra ≈varying mix of A-F V (<1 Gyr) and G-K III (3 - 15 Gyr)
  (ii) **starburst galaxies** (≈25% of local SF) range from :
  few $M_\odot$ yr^{-1} (SB) → ≈50 $M_\odot$ yr^{-1}(LIGs) → $10^{2\text{-}3}$ $M_\odot$ yr^{-1} (ULIGs)

Question: The Milky Way galaxy has about 5e9 solar masses of gas in total. If 2 solar masses of that gas is turned into stars each year, how many more years could the Milky Way keep up with such a star formation rate?

Answer: $5\text{x}10^9$ divided by 2 is $2.5\text{x}10^9$.
So, the MW can keep up its star formation rate of 2 solar masses per year for $2.5\text{x}10^9$ years.

How To:

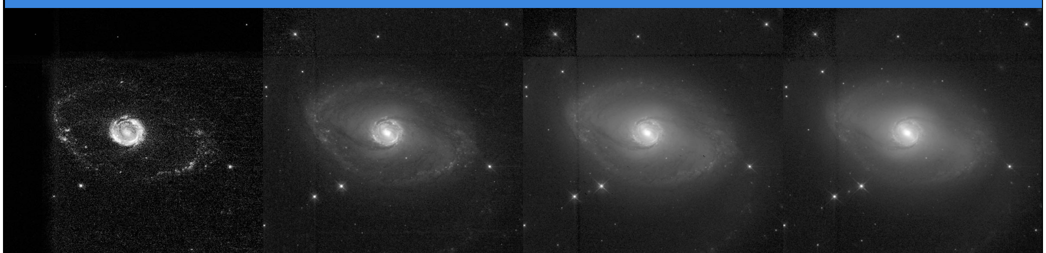
Measure & Characterize Extragalactic SF:

SFR - Rate (per year; per area)
SFH - History (Continuous/Steady, Instantaneous)
SFE - Efficiency (Gas Conversion)
(Location)

Integrated Measurements, Not Individual Stars
→ Synthesis Models (IMF,Metallicity,SFH,Age)

How to measure

Real Data:
- Line Emission (& Absorption)
- Broad Band



U B g r

Current Star formation in Galaxies

Observables

- Broadband optical colours
- Hα observations, which gives the number of ionizing photons (assuming all of these photons are used and eventually re-emitted)
- Far-IR flux, which assumes that a constant fraction of emitted stellar energy is absorbed by dust
- Radio continuum- this statistically correlates with far-IR flux, though underlying reason is complex
- Far-UV flux, which is primarily emitted by young hot stars
- X-ray emission, produced by high mass X-ray binaries (NS or BH with a massive companion)

• Star formation- UV emission

- The youngest star emit the bulk of their energy in the rest-UV
- UV Continuum is a direct meaure of the total luminosity of young massive stars

Major problems:

- However, dust attenuation prevents us from reliably measuring this emission
- At low redshift, have to observe from Space
- Very sensitive to the initial mass function (IMF)

UV image of the Andromeda Galaxy, taken by GALEX, shows how hot, young stars lie in ring-like structures

Star formation- X-ray view

In a star-forming galaxy, X-rays are produced by:

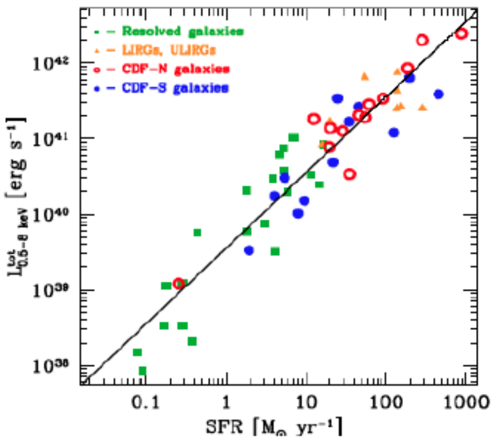
- High mass X-ray binaries, with a mean lifetime of 2 x 10^7 yr
- Hot gas from Supernovae (about 5% of the SN energy is required to produce diffuse X-rays

Advantage of X-rays:

Do not need to be concerned about dust, so can measure SF at high redshift

Disadvantage of X-rays:

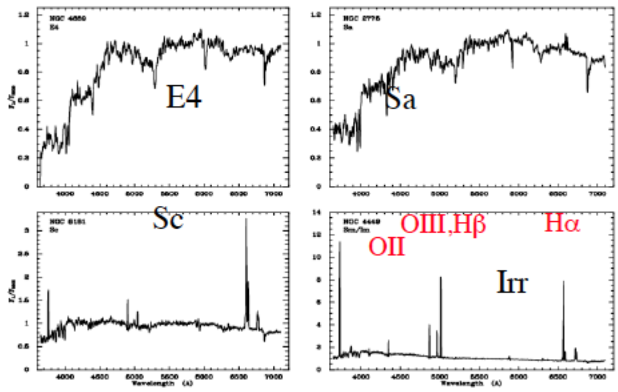
AGN also produce X-rays



Mineo et al 2012

Importance of emission lines

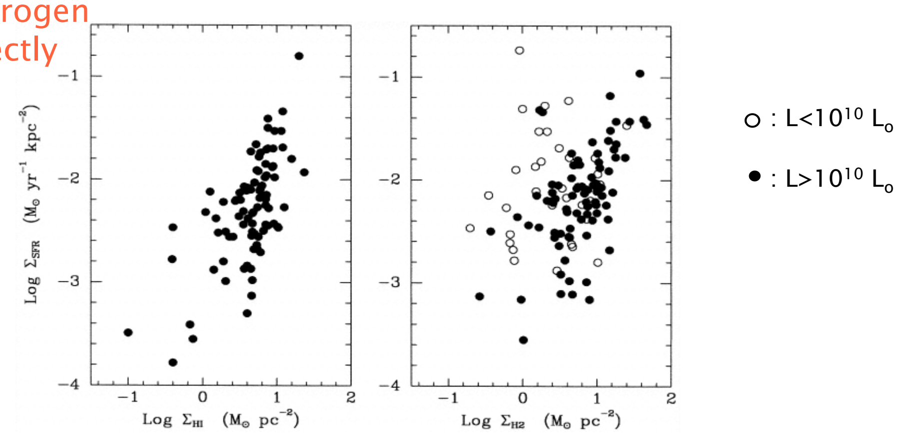
- As one moves across the Hubble sequence, emission lines become more dominant
- Some lines are produced by other phenomena
- E.g., Many authors use H and OII as SF indicators (and not OIII which is also produced by AGN and so it is difficult to separate AGN from SF)



Kennicutt 1998

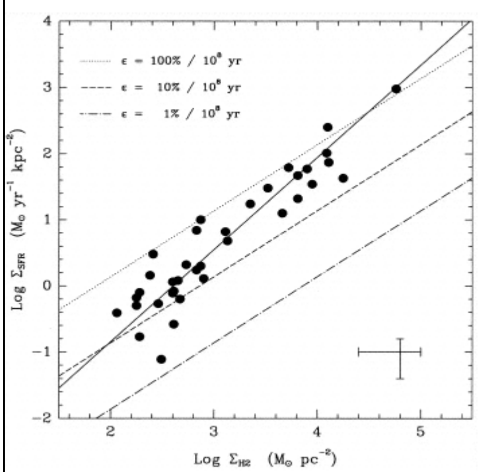
We can't detect molecular hydrogen directly

SFR based on $H\alpha$. H_2 densities based on constant CO/H_2 conversion factor.



Kennicutt 1998, ApJ 498, 541

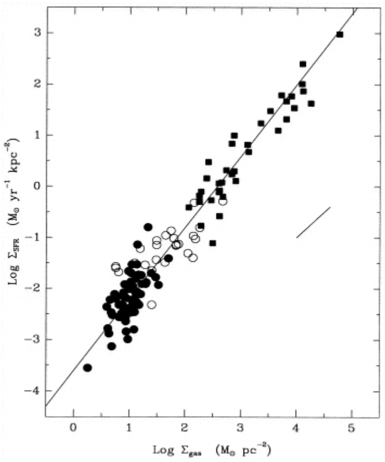
IR selected nuclear starbursts.
SFR based on FIR luminosities



Kennicutt 1998, ApJ 498, 541

Increasing star formation efficiency with increasing H_2 surface density

Composite SFR law for normal disk galaxies, nuclear regions of normal disks and starbursts



■ Starbursts

● Normal disks

○ Centres of normal disks

= 1.40

$$\Sigma_{SFR} \propto \Sigma_{gas}^{N}$$

Kennicutt 1998, ApJ 498, 541

Abundance and metallicity

[Fe/H], [O/Fe] etc.

Notation: [ ] denotes logarithmic ratio. […]=0 corresponds to solar abundance.
E.g. [Fe/H]=1 means an iron abundance 10x solar.

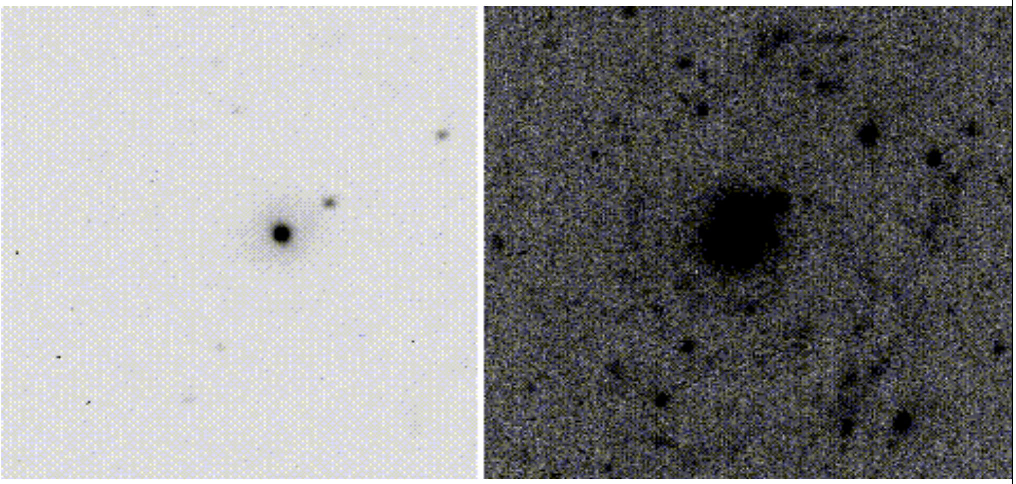
Solar abundance ratios include contributions from type I and II supernovae.

At very early times, [Fe/H]=negative (e.g. =-1.5) since the heavy elements have not be created yet,

Type II Supernovae occur at earlier times. They produce both O and Fe and so [O/Fe] is >0 (i.e. higher than the solar ratio).

At later times, type I Supernovae make more heavy elements. they contribute to Fe, but not to O. So the ratio [O/Fe] decreases at later times, when the metallicity of stars is higher.

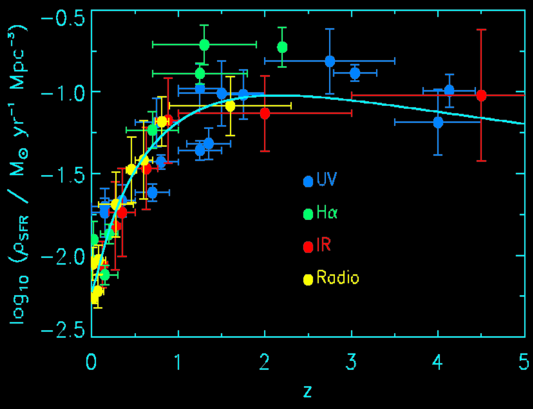
Caution:
Malin I – disk at the threshhold



Low surface brightness – LSB
Scaling relations don't work

How to kill a galaxy

Why Does Star Formation Stop?



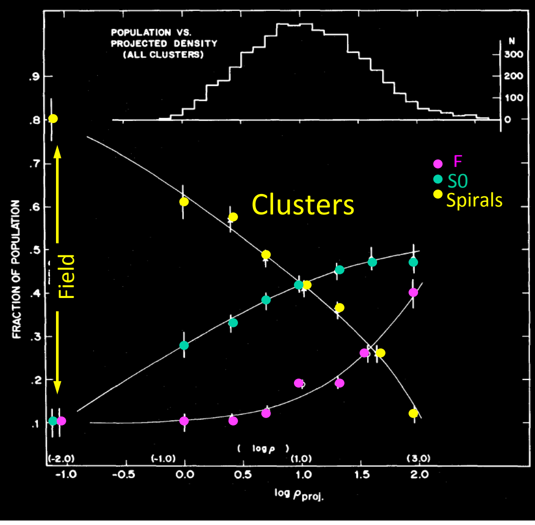
A) Internal? i.e. gas consumption and "normal" aging

B) External? Hierarchical build-up of structure inhibits star formation

Galaxy clusters: the end of star formation?

- "Dead" galaxies (i.e. little gas or star formation) found in rich clusters
- Hierarchical formation models predict number of clusters increases with time.
- So perhaps dense environments are responsible for terminating star formation?

Morphology–Density Relation



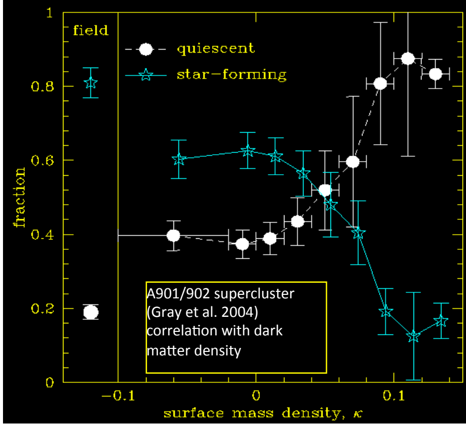
Dressler 1980

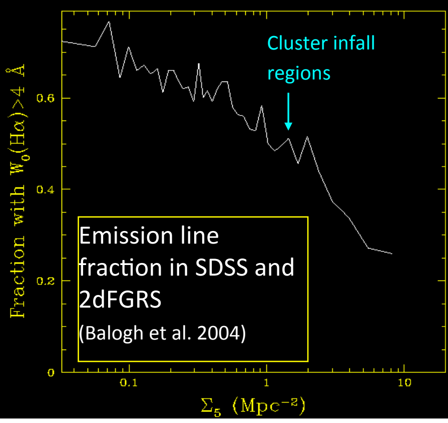
Nature or Nurture?

- Nature? Elliptical galaxies only form in protoclusters at high redshift. Rest of population is due to infall.
- or Nurture? Galaxy evolution proceeds along a different path within dense environments.
  - If this is true in groups and clusters, then environment could be the driving force of recent galaxy evolution…

Star formation

- Fraction of emission-line galaxies depends strongly on environment, on all scales
- Trend holds in groups, field, cluster outskirts (Lewis et al. 2002; Gomez et al. 2003)
- Fraction never reaches 100%, even at lowest densities



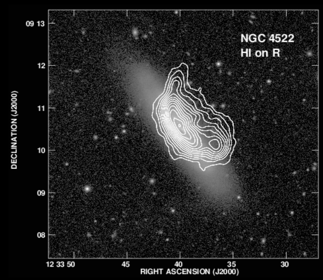


Additional physics?

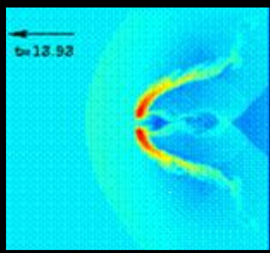
- Ram-pressure stripping (Gunn & Gott 1972)
- Collisions / harassment (Moore et al. 1995)
- “Strangulation” (Larson et al. 1980; Balogh et al. 2000)

Additional physics?

- **Ram-pressure stripping**
- Collisions / harassment
- "Strangulation"

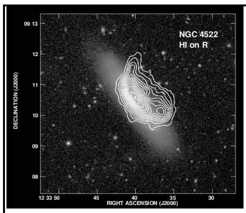


Kenney et al. 2003



short timescale

Quilis, Moore & Bower 2000



Ram Pressure stripping

Condition for ram pressure stripping

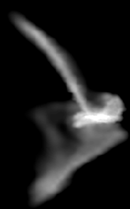
$$P \sim \rho v^2 > 2\pi G \Sigma_* \Sigma_{\rm gas}$$

Where Σ_* and Σ_{gas} are surface densities of the stellar and gas components of the galaxy.

v is the relative velocity of the galaxy and the inter-galactic medium, so the faster the galaxy moves, the more efficient the stripping process.

Additional physics?

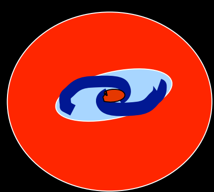
- Ram-pressure stripping
- Collisions / harassment
- "Strangulation"



important in groups?

Additional physics?

- Ram-pressure stripping
- Collisions / harassment
- "Strangulation"
  - Tidal disruption of the hot hydrostatic gas halo which would normally cool to replenish the ISM reservoir within the galaxy (e.g. Springel & Hernquist 2001).



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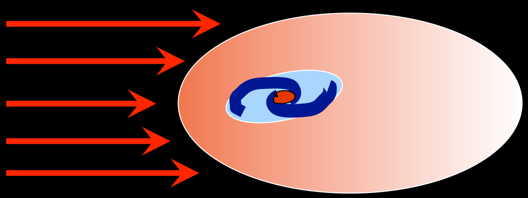
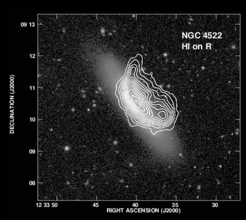
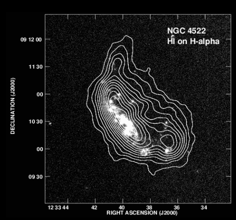


SF will then shut down on a long timescale, after star formation exhausts the existing ISM reservoir.

S to S0 transformation?





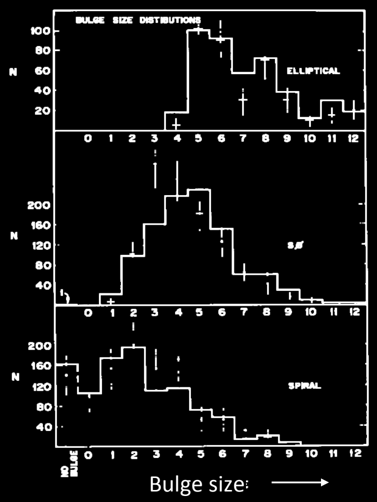
Kenney et al. 2003

Vollmer et al. 2004

- Ram pressure stripping of the disk could transform a spiral into a S0 (Gunn & Gott 1972; Solanes & Salvador-Solé 2001)

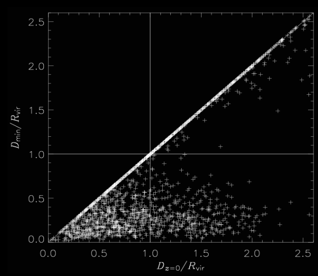
- Strangulation may lead to anemic or passive spiral galaxies (Shiyoa et al. 2002)

S to S0 transformation?



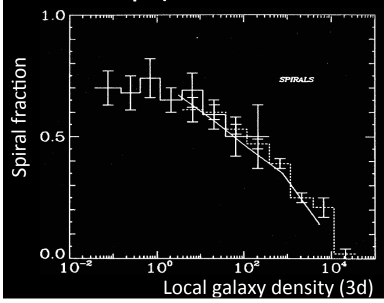
Dressler 1980

- But bulges of S0 galaxies larger than those of spirals (Dressler 1980; Christlein & Zabludoff 2004)
- Requires S0 formation preferentially from spirals with large bulges (Larson, Tinsley & Caldwell 1980) perhaps due to extended merger history in dense regions (Balogh et al. 2002)



Gill et al. 2004

Groups (Postman & Geller 1984)



Arguments against ram pressure stripping:

1. S0 galaxies found far from the cluster core
   - Galaxies well beyond R_{virial} may have already been through cluster core (e.g. Balogh et al. 2000; Mamon et al. 2004; Gill et al. 2004)

2. Morphology-density relation holds equally well for irregular clusters, centrally-concentrated clusters, and groups

   - but may be able to induce bursts strong enough to consume the gas

Summary

- Star formation occurs in molecular clouds in galaxies
- Mergers and tidal interactions between galaxies can cause star formation in the core or distributed all over the galaxy
- The current rate of star formation can be measured from optical colours, UV fluxes (problem: extinction), far-IR fluxes, radio continuum or X-ray fluxes
- Star formation can be quenched by environmental effects. In a cluster, for example, physical processes like ram pressure stripping, strangulation or harassment can cause star formation to cease.