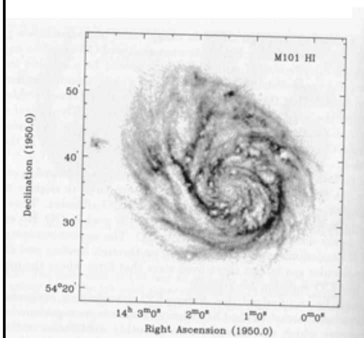
Molecular clouds

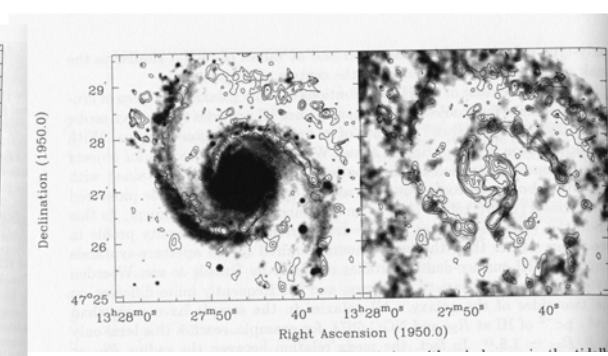
(see review in astro-ph/990382)
(also CO [12.1,12.2])

- Massive interstellar gas clouds
  - Up to ~10^5 $M_\odot$
  - 100's of LY in diameter.
  - Giant Molecular Clouds (GMCs) defined to be $M > 10^4$ $M_\odot$
- High density by interstellar medium standards
  - Up to 10^5 atoms per cm^3
- Shielded from UV radiation by dust, so atoms are combined into molecules.
  - H_2 not easily detectable
  - but also H_2O, NH_3, CO plus much more complex molecules.
    - These form emission lines in observable passbands
    - CO is usual tracer.
      - mm wave observations (➔ low angular resolution)
- All stars form in molecular clouds.
  - Vast majority form in GMC's.

M51



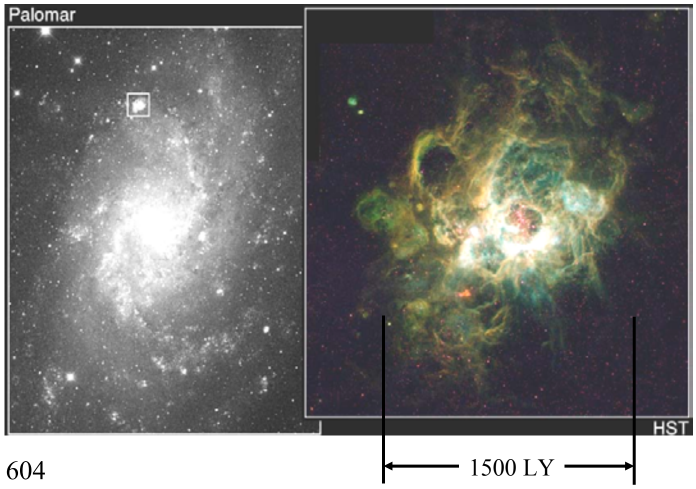
21 cm map



CO contours over red image

CO contours over 21 cm map

Star-forming region in M33

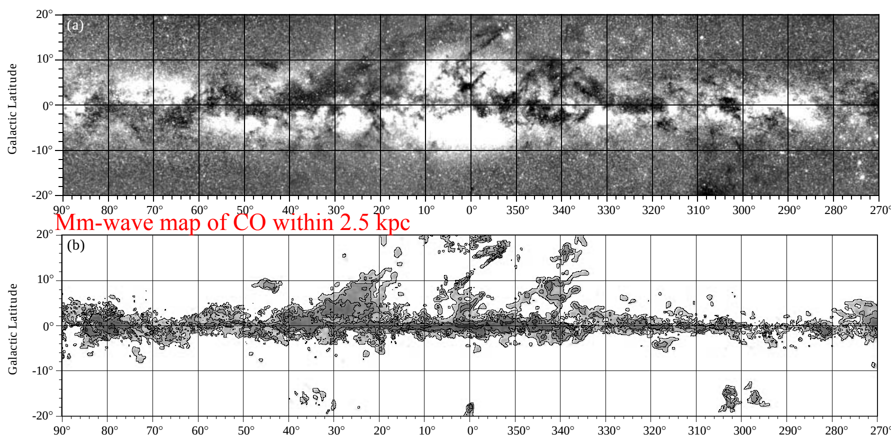


- NGC 604
  - Vast complex of molecular clouds & HII regions.
  - In outer spiral arms of the nearby galaxy M33.
  - Contains 200 O stars.

CO map of Milky Way

Dame, Hartmann & Thaddeus (2000, ApJ)

Optical (l_{II} = +/- 90°)



Mm-wave map of CO within 2.5 kpc

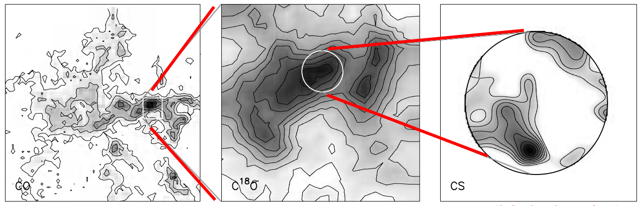


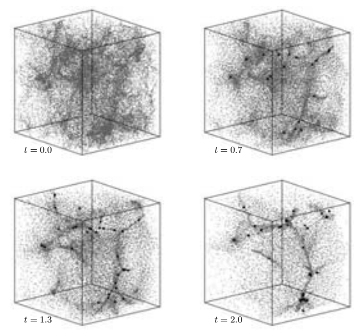
Figure 4. Hierarchical cloud structure. The three panels show a representative view from cloud to clump to core. The bulk of the molecular gas (cloud; left panel) is best seen in CO which, although optically thick, faithfully outlines the location of the H_2. Internal structure (clumps; middle panel) is observed at higher resolution in an optically thin line such as $C^{18}O$. With a higher density tracer such as CS, cores (right panel) stand out. The observations here are of the Rosette molecular cloud and are respectively, Bell Labs (90″), FCRAO data (50″), and BIMA data (10″).

Model of evolution of box containing 222 x Jeans masses (1000 $M_\odot$) breaking up into clumps.
➔ proto-stellar cores giving ~ IMF slope.

R. Klessen & A. Burkert: *Fragmentation in Molecular Clouds* 3

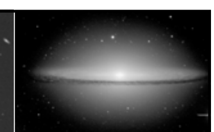
Complex internal structure

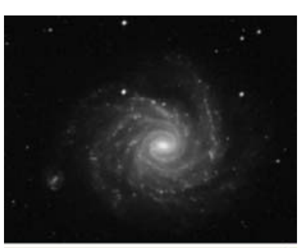
- MCs are > 50% molecular gas by mass.
- but only ~ 20% by *volume*.
- internal clumps and filaments
  - 100's of clumps in a GMC
- but most clumps not gravitationally bound
  - do not form stars
  - pressure-confined
- majority of stars form in clusters in a few of the most massive clumps.



M33 = Sc

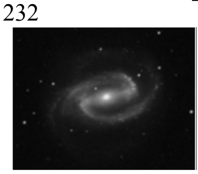
M31 = Sb





#4 NGC 1232

S0	0
Sa	6
Sb	2
Sc	14
Sd	0
Other	0



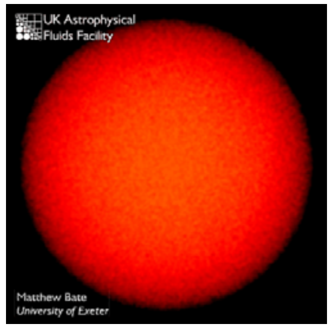
#5 NGC 7331

S0	1
Sa	5
Sb	15
Sc	1
Sd	0
Other	0

#6 NGC 3623

S0	5
Sa	13
Sb	0
Sc	2
Sd	1
Other	1

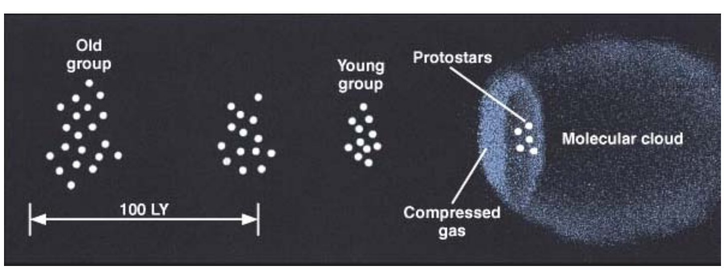
Computer simulation of Star Formation in a Molecular Cloud



By
Matthew Bate,
University of Exeter
UK

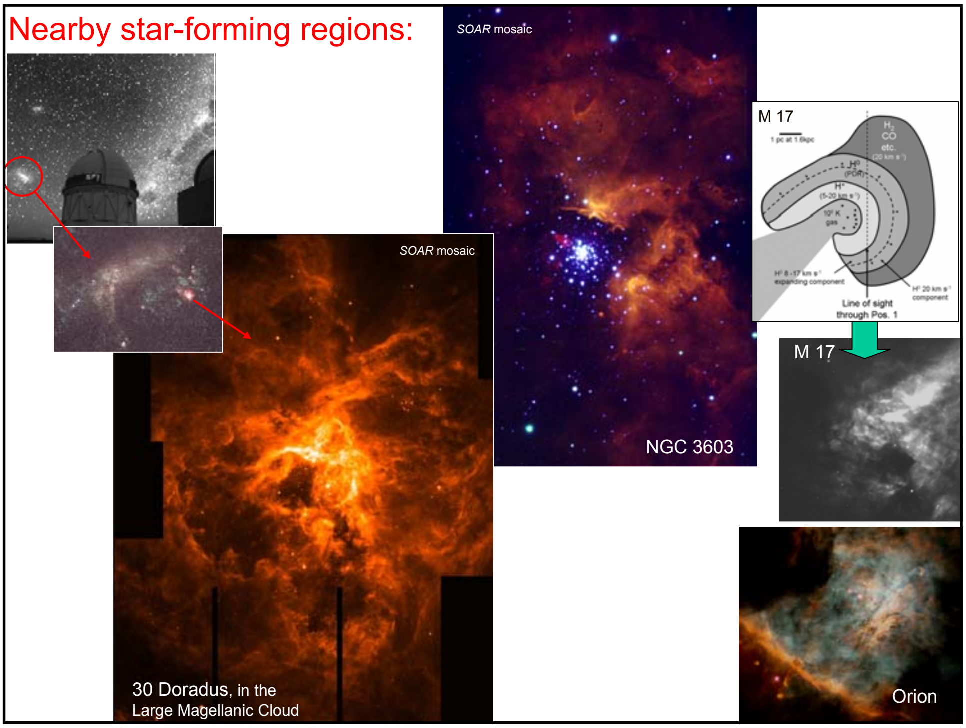
- Collapse and fragmentation of 50 solar-mass cloud.
  - Initially 1 light-year in diameter.

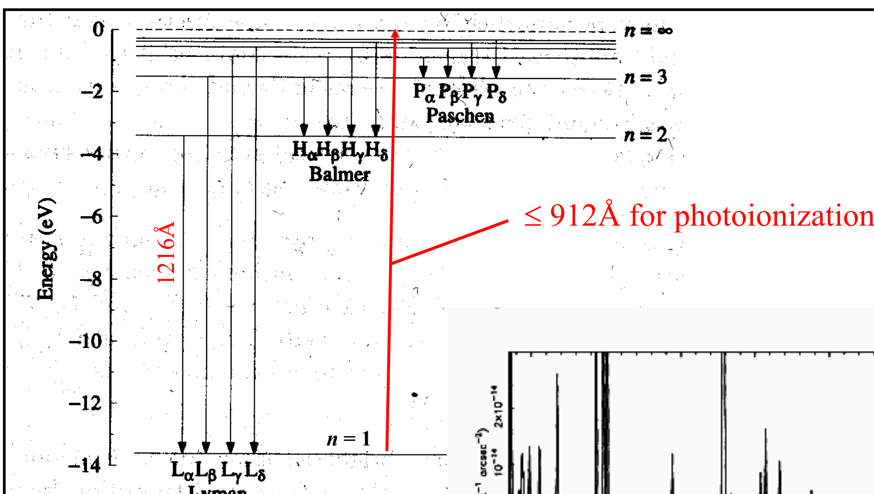
Star formation thought to propagate in wave through dense molecular clouds

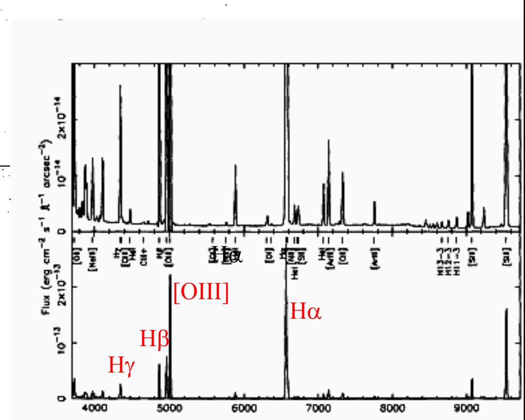


- Photons from very luminous O stars heat and blow away surrounding gas.
- So slightly older clusters no longer shrouded by dusty gas
- Compression of gas further inside cloud causes inward wave of star formation ("triggered" star formation).

Nearby star-forming regions:

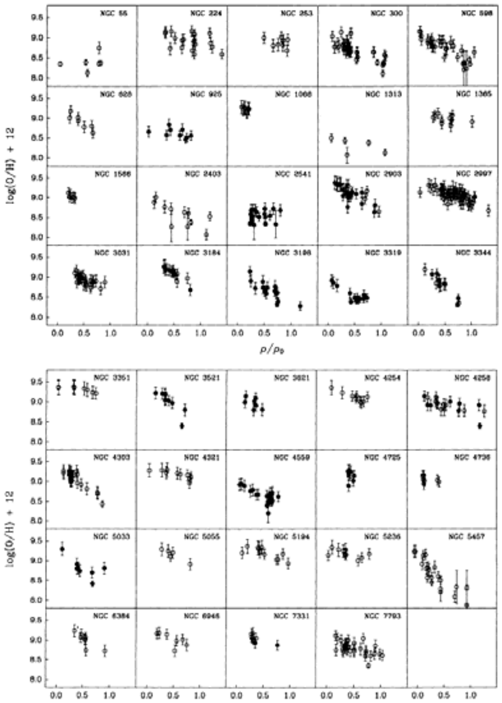






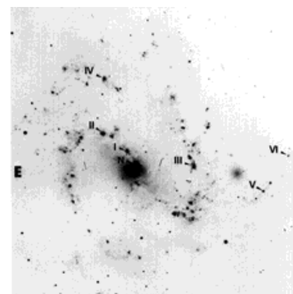
Spectra of HII Regions

- Gas temperature
- Gas density
- Mass of ionized gas
- Star formation rates.
- Relative chemical abundances.

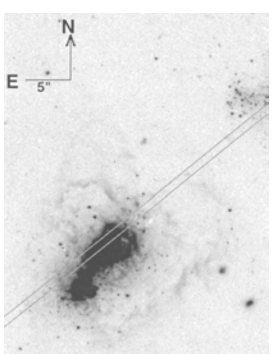


Abundance Gradients in Spiral Galaxies

- From Zaritsky et al (1994) ApJ 420, 87.
- O/H abundance ratio as function of radial distance from nucleus.
- 39 spiral galaxies.
- Measured from HII regions.



Primordial Helium Abundance



Use Blue Compact Dwarf galaxies
(dwarf Irr galaxies undergoing initial star bursts)

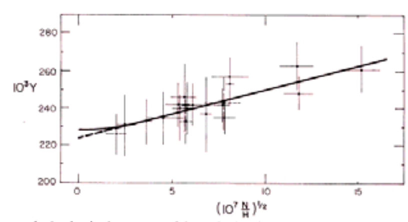


Figure 1. Helium mass fraction plotted against square root of nitrogen abundance for the data sample of Pagel *et al.* (1992). The broken line represents a weighted least-squares linear regression (taking into account errors in both coordinates as was done by Mathews *et al.*: $Y = 0.224(\pm 0.007) + 8.11\,(N/H)^{1/2}(\pm 2.65$ s.e.). The solid curve is deduced from the He–O regression of Pagel *et al.* (1992) and the (N/O–O/H) relation shown in Fig. 2.

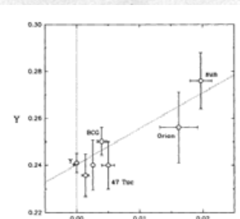


FIG. 18.—Current status of the dY/dZ relation. The value for Orion is from this work. The solar value is from Turck-Chièze et al. (1988). The point for 47 Tuc is from Dorman et al. (1989), and the points for blue compact galaxies (BCG) and the primordial helium abundance are based on the review by Olive (1990).

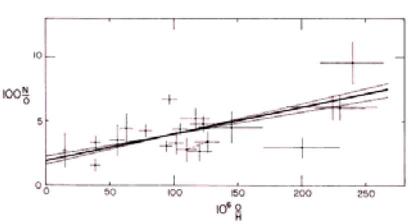
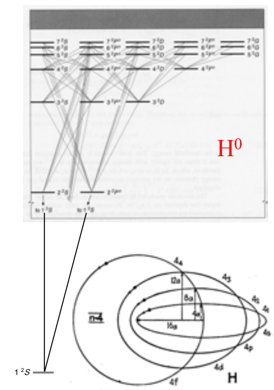


Figure 2. Relation between N/O and O/H for the data set of Pagel *et al.* (1992) with the maximum likelihood linear regression: $N/O = 0.0193(\pm 0.0032) + 206\,(O/H)(\pm 32$ s.e.), and $\pm 1\sigma$ equivalent confidence limits.

Permitted vs. Forbidden Emission Lines

- Emitted photon carries both energy & angular momentum.
  - atom must supply both correct ΔE and Δl
  - + Pauli exclusion principle: no 2 electrons can have same values for all 4 quantum numbers: **`n,l,s,m`**
- *Permitted transition:*
  - Simple electric-dipole radiation.
  - Parity of wavefunction changes.
- *Forbidden transition*:
  - Electric quadropole, magnetic dipole.
  - Parity stays same ➔ lower probability.
- Probability expressed as *inverse lifetime* in upper level: A_{ij}
  - Permitted transitions: Hβ, Lyα, HeII 4686, etc. $1/A \sim 10^{-8}$ s
  - Forbidden transitions: [OIII] 5007 1/A = 48 s
    [OII] 3726 1/A = 5500 s
    [NII] 6584 1/A = 330 s
    etc.
- In dense gases (photospheres, Earth's atm. at sea level, etc.)
  - Collisional de-excitation timescale << 1/A of forbidden lines.
- In HII regions
  - Collisional de-excitation timescale ≈ 1/A of forbidden lines.



Hydrogen orbits, n=4.
Different **`l`** ➔ different angular momentum