Fluids in Astrophysics

Astrophysical fluids are mainly in gaseous and plasma form

The cosmos is pervaded by gas – fluids are everywhere

Average matter density of the universe: 1.5×10^{-27} kg / m^3

Most (>85%) of this is dark matter. The rest is ordinary matter

Mass density in ordinary matter (baryons) is 2×10^{-28} kg / m^3
≈ 0.1 baryons / m^3 (number density)

Dark matter is cold and pressureless – behaves like "dust"

Fluid behaviour is displayed by the baryonic component

Baryonic fluid in the present-day universe

Average number density ~ 0.1 atom / m^3, average temperature ~ 3 K
Composition (mass fraction) ~ 71% H, ~ 27% He, ~ 2% “metals”

=> In atom count, ~ 90% is Hydrogen

~75% (mass fraction) Hydrogen and ~25% Helium was synthesised in the early universe, within ~3 minutes of the Big Bang. Metals, and more helium, have been synthesised later in stars.

In the beginning, gas distribution was very smooth and uniform. Today the distribution is highly inhomogeneous and non-uniform in small scale. Physical conditions span a very wide range.

Collapsed structures: Planets, Stars, Galaxies, Clusters

Diffuse gas fills the space between collapsed structures

Stars and planets: Self-gravitating gas globes:

The Sun: central no. density ~ 10^{32} baryons/m^3, temperature ~ 10^7 K
average density ~ 10^{30} m^{-3}, surface temperature ~ 6000 K
compare: air on earth: ~ 10^{25} atoms / m^3

White Dwarf: no. density ~ 10^{36} m^{-3}

Neutron Star: no. density ~ 10^{45} m^{-3}

Jupiter: average density ~ 10^{23} m^{-3}

Diffuse matter:

Interplanetary medium: $n \sim 10^7\ m^{-3}$, $T \sim 10^5$ K

Material between stars in our galaxy (ISM): $n \sim 10^6\ m^{-3}$, $T \sim 10^4$ K

Material between galaxies (IGM): $n < 0.1\ m^{-3}$ - $n \sim 10^4\ m^{-3}$
$T \sim 10^5$ - 10^8 K
Hotter and denser IGM in clusters

Character of Astrophysical Fluids

Collision between particles is rare in the diffuse gases encountered in astrophysics

e.g. ISM: ~ 10^6 atoms / m^3 , T ~ 10^4 K

Collisional mean free path:

neutral: ~ 10^{14} m ≈ 1000 times the Earth-Sun distance

ionized: ~ 10^{11} m ≈ Earth-Sun distance

Can this be considered a fluid?

In a fluid, the length scale of variation of physical quantities
(density, pressure, velocity)
must be much larger than the mean free path.

Often not satisfied for collisional mean free path in diffuse astrophysical fluids.
Momentum transport via magnetic field very important

Magnetic fields

Magnetic fields are ubiquitous in the cosmos

ISM: $B \sim 10^{-6}$ G.
Larmor radius: electrons $\sim 10^{3}$ m, protons $\sim 10^{7}$ m
much smaller than collisional mean free path

Interplanetary medium near the Earth: $B \sim 10^{-5}$ G

IGM: $B \sim 10^{-9}$ G
Magnetic field in these diffuse media are usually quite tangled

Jupiter: ~10 G; Sun: ~1G dipole, $\sim 10^{3}$ G sunspots
Magnetic stars: $\sim 10^{3}$ G dipole
White Dwarfs: up to $\sim 10^{6}$ G; Neutron Stars: 10^{8} - 10^{15} G

Magnetic fields and ionised plasma make MHD the appropriate description for the dynamics of Astrophysical Fluids.

Ionisation of hydrogen in astrophysical conditions

Ionisation potential E_i = 13.6 eV ; $T_i = E_i / k_B = 1.6 \times 10^5$ K

Ionisation equilibrium dictated by the Saha ionisation equation

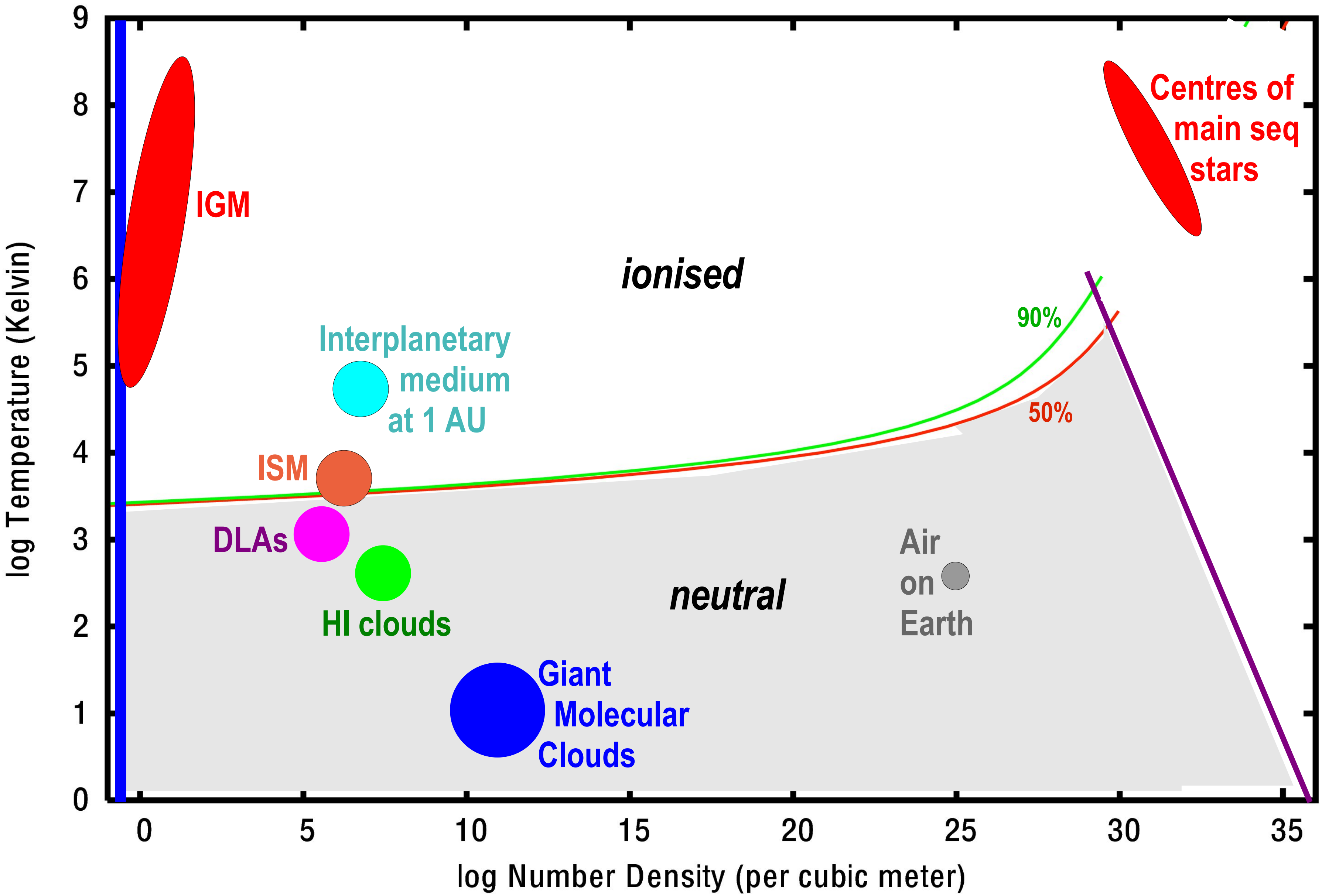
$$\frac{n_e n_p}{n_H} = \left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} \exp(-T_i/T)$$

Gives the remarkable result that hydrogen plasma is fully ionised at $T \sim 0.1\, T_i$ for a very wide range of densities.

If $n > 10^{30}\ \mathrm{m}^{-3}$ then pressure ionisation dominates.

Most of the diffuse astrophysical gas we encounter is thus ionised. Notable exceptions are HI clouds and molecular clouds in the ISM.

Hydrogen Ionisation



Evolution of cosmic gas

We live in an expanding universe. In the past, the universe was smaller and denser. $a(t)$ = the scale factor of the universe; redshift $z = a(t_0)/a(t) - 1$ is a measure of look-back time.

Density $\rho \propto (1+z)^3$; $T_{rad} \propto 1/a(t) \propto (1+z)$

At large z, matter distribution was very uniform.

Structures (e.g. stars, galaxies, clusters) have formed due to growth, via gravitational instability, of very small initial density perturbations.

Dark matter and baryonic matter behave differently. Dynamics of dark matter governed only by gravity and cosmological expansion. Baryonic component influenced by pressure and interaction with radiation.

Formation of Dark Matter halos

Dark matter overdensity $\delta\rho/\rho$ grows initially as $\propto a$

Due to self gravity, the overdense region expands progressively slower than Hubble flow

At some point, the expansion of the overdense region stops completely. It turns around and collapses when the average density of the region reaches ~ 6 times the background density. It then settles down to a virialized structure (halo) with density ~ 200 times the background density at the time of collapse.

Structures form hierarchically. Small scale halos form earlier than larger ones. Large halos result both from late turnaround of large length-scale perturbations and from merger of smaller halos.

Dark matter halos provide potential wells for baryons to fall into

Baryonic Fluid

At very large scales dark matter and baryonic matter follow each other. Perturbations grow the same way.

At scales below acoustic horizon pressure matters.
Tight coupling with background radiation prevents infall.

Radiation decouples when matter becomes neutral at z ~ 1000.

Baryonic fluid then falls into dark matter halos. Gets hot, radiates, loses energy and condenses even further to form galaxies. Further cooling, fragmentation and collapse forms stars within the galaxy. The first galaxies form around z ~ 10.

Radiation generated by stars and galaxies re-ionize the Intergalactic Medium.

In general, the time to reach thermal equilibrium is very long in the diffuse media encountered in astrophysics. Regions of different density and temperature may therefore co-exist. Pressure equilibrium is established much more quickly.

ISM in our galaxy has multiple phases in pressure equilibrium:

Molecular clouds: $n \sim 10^{8}\ \mathrm{m}^{-3}$; $T \sim 10$ K
HI clouds: $n \sim 10^{7}\ \mathrm{m}^{-3}$; $T \sim 100$ K
Warm Neutral Medium: $n \sim 10^{6}\ \mathrm{m}^{-3}$; $T \sim 1000$ K
Warm Ionized Medium: $n \sim 10^{5}\ \mathrm{m}^{-3}$; $T \sim 10^{4}$ K
Coronal gas: $n \sim 10^{3}\ \mathrm{m}^{-3}$; $T \sim 10^{6}$ K

Expanding overpressure regions are produced by

- Hot stars – ionisation, winds
- Explosions – novae, supernovae, GRBs

Heating and cooling of cosmic gas

Important heating sources:

- Ionising radiation field
- Cosmic rays
- Mechanical energy input (e.g. Winds, Supernovae, Jets, Bubbles)
- Gravitational infall
- Nuclear energy release

Important cooling processes

- Radiation – bremsstrahlung, line cooling
- Scattering – Compton cooling
- Mechanical – expansion cooling