Australian National University

# ASTR2013 – *Foundations of Astrophysics*

# Week 7: The Interstellar Medium and Star Formation

Mike Ireland

# Field Trip Follow-Up

- Drop-in sessions. These have now been requested formally by your student representative. We can have them 19 Sep (Thursday), one of 26 or 27 Sep (Thurs/Fri before problem set and Field trip report due) and 10 or 11 Oct (Thurs/Fri before 2$^{nd}$-last problem set due). VOTE NOW
- However *tutorials remain the most important times for getting help.*
- Overall, feedback would be useful – I've already mentioned that we'll do everything we can to accommodate the class of 2020 on the mountain (observatory purchasing extra beds etc).

# Field Trip Follow-Up

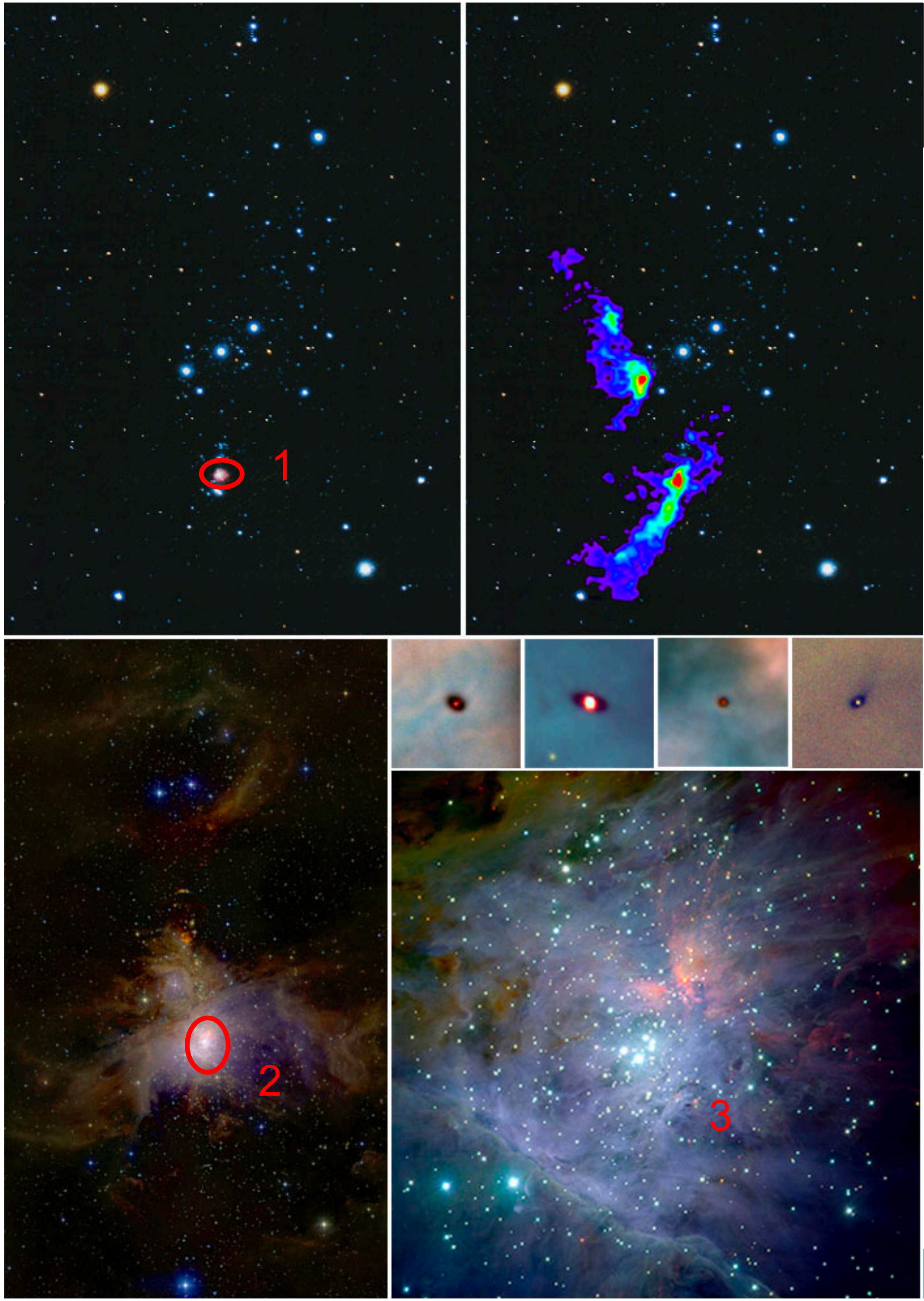
- For the field trip report, instructions and Due Date (31 Oct) are on Wattle – reports should be individual, but work should be as a group. Everyone has to say which part of the group work they did.
- Data reduction and analysis is ongoing. All groups should have enough to complete the data "reduction" and make plots by the end of today's tutorial. Please:
  - Check both anu365 and Wattle.
  - Add your observing log and notes to Wattle
  - Meet with your group in addition to the tutorial times.

# Week 7 Summary

Textbook: Sections 5.1, 5.2 and 5.3 (5.4 is also great, but Naomi will cover this in ASTR3013 next year)

1. The Jean’s Mass.
2. The Strömgren Sphere.
3. Gas heating and cooling mechansms.
4. Components of the Interstellar Medium

Additional reference: Mark Krumholz’s textbook available for free at https://arxiv.org/abs/1511.03457.




- Zoom in to a star forming region…(e.g. Orion)
- Cold gas collapses to form stars, which in turn locally heats the gas to ~7000K
- *How does the gas collapse? What determines its properties?*

# Jean’s Mass (side comment)

- The “Jean’s Mass” is the mass of a cloud of gas that can collapse under its own gravity.
- There are many derivations of the “Jean’s mass”, partly because the 52 page paper published in 1902 is a very difficult read.
- Most modern derivations use partial differential equations (MATH2306) to derive the wave equation for a self-gravitating gas of (locally) uniform density:

$$\omega^2 = c_{\rm is}^2 k^2 - 4\pi G \rho_0$$

- Short wavelength waves are like sound waves, but long wavelength waves are unstable and grow.
- For this course, please focus on the textbook derivation…

# Jean's Mass

- Assume there is a cloud of ideal, non-relativistic gas of uniform temperature and density.
- On the board, we can consider what happens to the internal gravitational and thermal energy of the cloud if the radius changes by a small amount.
- If the gravitational energy changes by more than the thermal energy, the cloud will be unstable to collapse, and we derive a critical mass:

$$M_J = \frac{3k_B T}{G\bar{m}} r = \frac{3c_s^2}{G} r$$

# Jean’s Density and Scaling

- The critical density for collapse depends strongly on the cloud mass – solar mass clouds have to be much more dense:

$$\rho_J = \frac{M}{\frac{4}{3}\pi r_J^3} = \frac{3}{4\pi M^2}\left(\frac{3kT}{G\bar{m}}\right)^3 .$$

- Observed cold gas clouds have a mass of around 1000 $M_{sun}$, a temperature of around 20K and an measured density at least $10^2$ particles/$cm^3$.
- The Jean’s density is then ~1 particle/cm3, meaning that the cold gas clouds should be unstable to collapse.
- Note that a 1 $M_{sun}$ part of the cloud is stable – individual stars should not form from the collapse of clouds of typically observed densities and temperatures.

# Cloud Collapse and Fragmentation

- Remember the free-fall timescale:

$$\tau_{\rm ff} \sim \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$

- A uniform density cloud has a single timescale, and would collapse until it became optically-thick (and heated up).
- A cloud that starts off more dense in the center (or elsewhere) collapses faster in the more dense parts.
- As density increases, smaller parts of the cloud become Jeans unstable, resulting in collapse inside a collapsing cloud: *fragmentation.*

# Cloud Collapse and Fragmentation

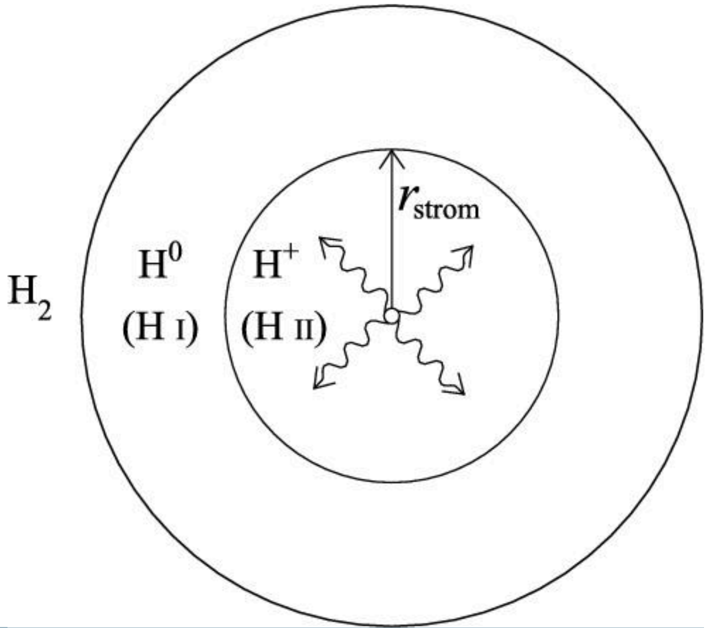
- The collapsing cloud is kept at a near-constant temperature by two key processes:
  - Radiative cooling, especially in optically-thin gas (reminder of what this is on board – what is the limiting column density for typical opacities?)
  - Dissociation processes in the gas that absorb energy.
- The energy involved in this dissociation is significant: 4.5 eV per molecule to dissociate $H_2$, and 13.6 eV per atom to ionize H.
- These processes alone can absorb the energy needed for a 1 $M_{sun}$ star to collapse to 0.3 au (see textbook or equate the energy yourself!).

# End Result – Star Clusters

- The outside-in collapse, or top-down fragmentation of gas clouds means that stars very rarely form alone  - typically stars form in large associations.
- If the associations are still gravitationally bound after gas disperses, the result is a *star cluster* as seen on the field trip.

# Strömgren Spheres

- Once a massive stars form, they can start emitting emitting strong UV radiation on a timescale even shorter than the cluster free-fall time.
- This radiation heats up local gas, preventing collapse in part of the cluster.
- The radius of ionized gas is called the Strömgren radius.
- $r_{strom}$ is determined by the balance between photo-ionization and recombination (via collision)



# Strömgren Spheres

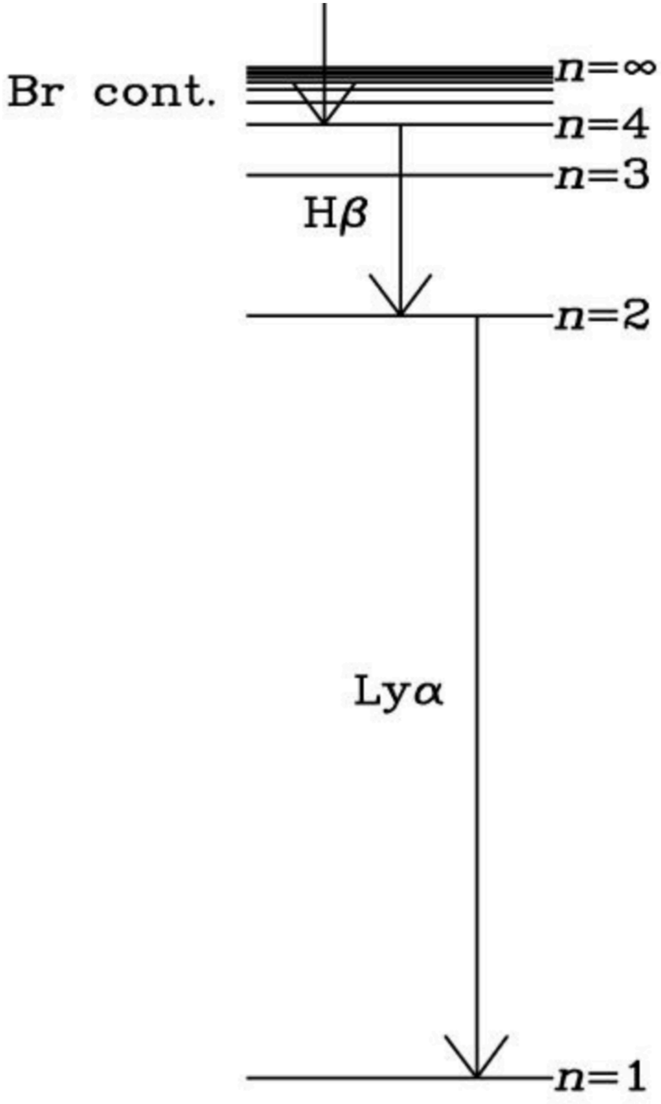
- Only photons with energies about 13.6eV can ionize H. We call the rate of emitted photons Q*, and the recombination rate $R_{\mathrm{rec}}$ per unit volume.
- Then we have: $$Q_* = \mathcal{R}_{\mathrm{rec}} \frac{4}{3}\pi r^3,$$
- The recombination rate depends on temperature and the number of collisions:

$$\mathcal{R}_{\mathrm{rec}} = \alpha(T)n^2$$ (assuming nearly ionized gas)

- This results in: $$r_{\mathrm{strom}} = \left(\frac{3Q_*}{4\pi\alpha n^2}\right)^{1/3}.$$

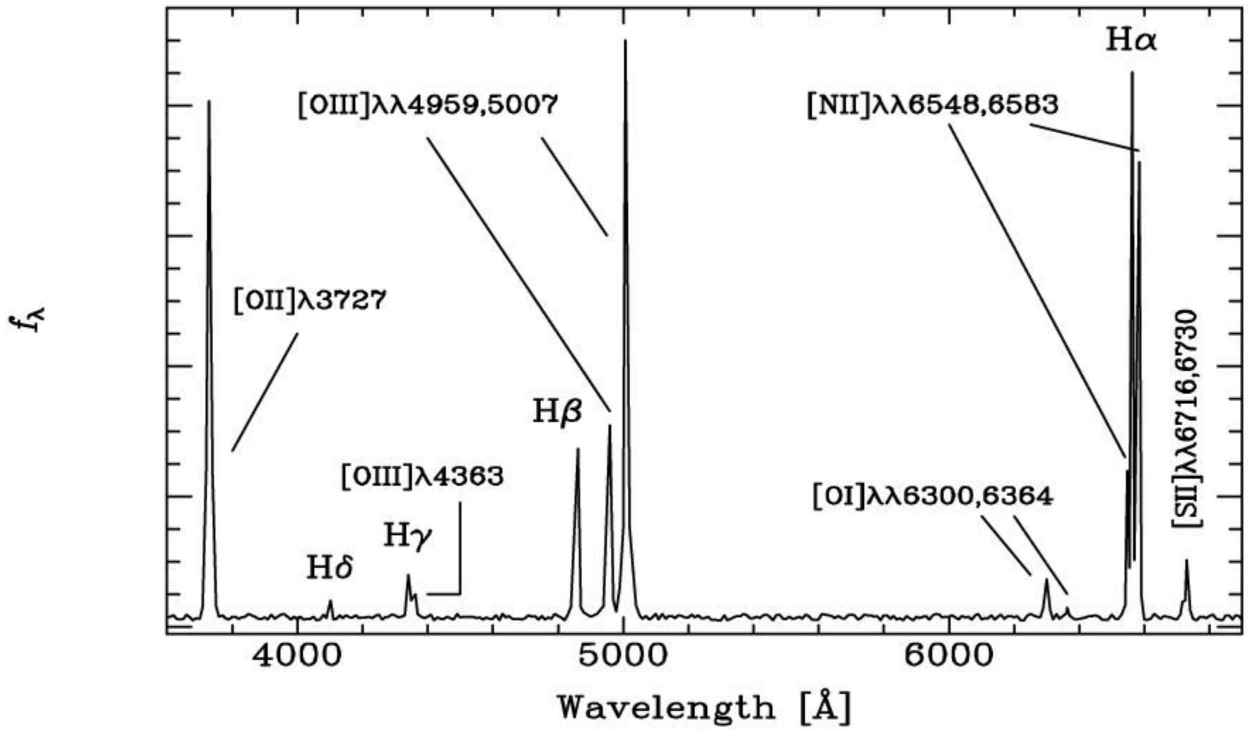
# Heating and Cooling

- Outside the Strömgren sphere, photons are absorbed very rapidly, resulting in a sharp transition.
- Inside the Strömgren sphere, energy can be lost by:
  - Balmer series photons (e.g. “pink” Ha) that emit recombination energy but can’t be re-absorbed.
  - Collisionally excited heavier atoms (especially Oxygen, the 3rd most abundant element).
  - “Free-free” or “Bremsstrahlung” emission, which is most relevant at longer wavelengths and dense regions, or very high temperatures.



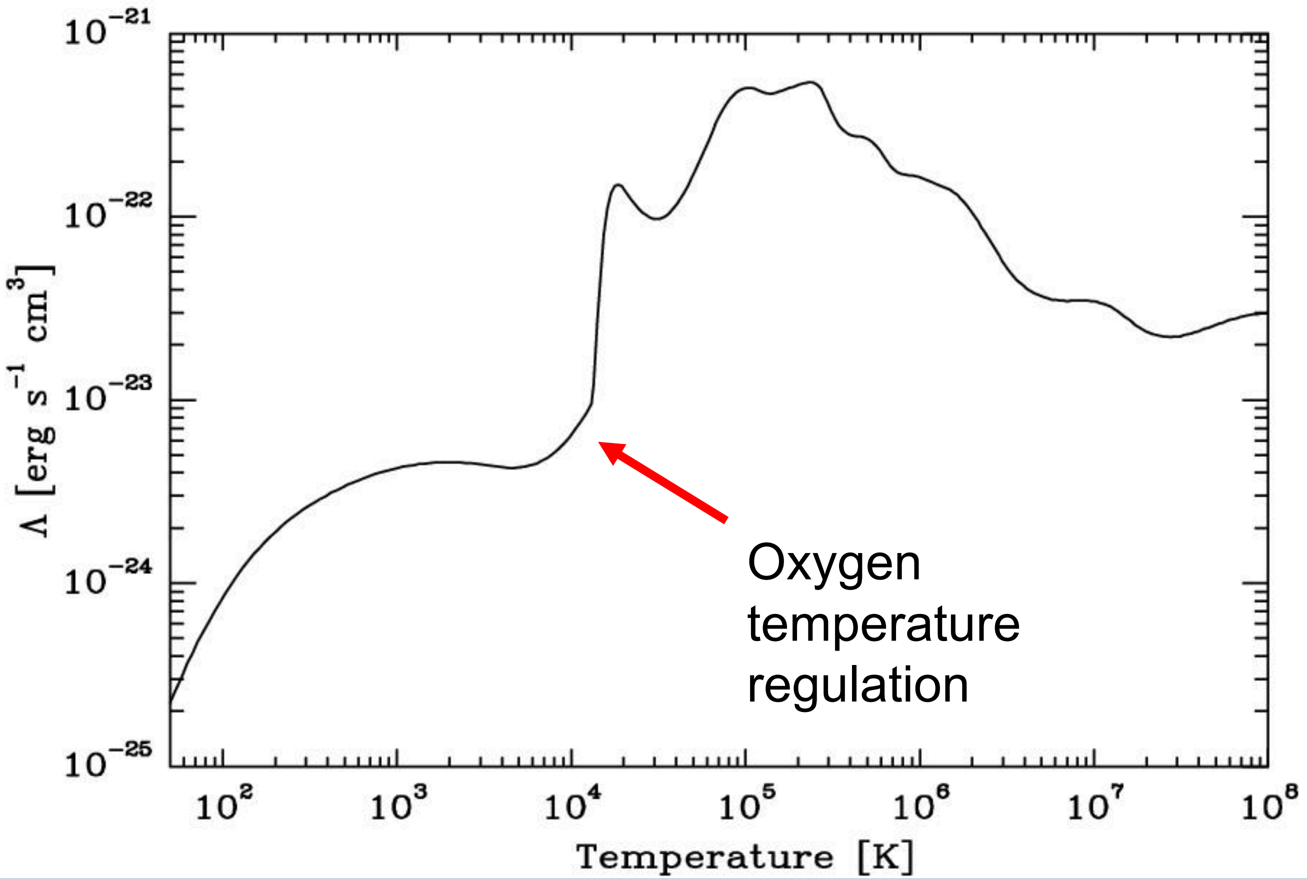
# Heating and Cooling

- The observed spectrum of a HII region (ionized H, where neutral H is HI) is then dominated by photons that result in cooling.
- Many other photons are emitted and re-absorbed within the HII region, but only ones that can escape are seen.
- These are *forbidden* transitions, given square brackets in conventional spectroscopic notation, like [OII].



# Heating and Cooling

- Heating of electrons happens e.g. when photons have more energy than they need to ionize hydrogen.
- The balance of heating with cooling determines the gas temperature. When cooling rises rapidly with temperature, there is a natural thermostat.



# Components of the ISM

- The ISM is stable in 5 main phases:
  1. Molecular hydrogen (~30K) in cool, star forming regions (small fraction of the Galaxy) – efficient cooling e.g. by dust and ice.
  2. Cold neutral gas (100K), seen by the hyperfine transition of Hydrogen (next week)
  3. Warm neutral gas (7000K) which is harder to see.
  4. Warm ionized gas (10,000K), seen by Balmer series and [O] lines.
  5. Hot ionized gas ($10^6$K), where cooling by atoms is not efficient (e.g. intergalactic medium.
- Additionally, dust is important at absorbing light, especially in Molecular and Cold Neutral phases.

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