RAFFREDDAMENTO DELLE REGIONI HII E DELLE NEBULOSE PLANETARIE –FORMAZIONE E RUOLO DELLE RIGHE PROIBITE

The main reference source for this note is the chapter 5 in the Dyson and Williams ("The Physics of the Interstellar Medium") book

Photoionisation feeds energy into the nebula gas since it creates hot, fast photoelectrons.
Without some ENERGY LOSS mechanisms the gas temperature would rise indefinitely.
Observational analysis of HII region spectra suggest electron temperatures of about 10 000 K (~10^4 K), significantly lower that the effective temperatures of the ionising OB stars.
If we have a pure H nebula, energy is released in H recombination. The KE of the recombining electron is converted to photons, which may escape from the nebula and cool it. However, by comparing the heating and cooling rates from this process we find that higher nebula temperatures are expected.

For a typical OB star T_e ~30 000-60 000 K, which is much higher that values of T_e ~10 000 K for nebulae derived from their spectra.
Inclusion of other possible H-cooling process still gives too high temperatures,
This implies that we have neglected some important cooling process . . .

Forbidden line cooling of HII regions (and PNe)

Real nebulae contain other elements than just Hydrogen. We must, therefore, relax our assumption of a pure H nebula. A special emission line formation process in "metals" *(ricordo che viene detto metallo qualsiasi elemento chimico che non sia H o He)* can give emission line radiation which can escape from the gas and cool it. This is called FORBIDDEN LINE emission.
Bound electrons in atoms can be excited/de-excited in two ways: by photons (resulting in absorption/emission) or by collisions (non-radiative process, meaning there is no way to 'see' it) between atoms or atoms and electrons.
The Balmer (n $\rightarrow$ 2) and Lyman (n $\rightarrow$ 1) transitions in Hydrogen are excited/de-excited by the absorption/emission of photons, and give rise to what are called ALLOWED transitions in quantum mechanics. The downward (de-excitation) transitions of electrons within the atom occur spontaneously with a very high probability (typical transition probabilities are ~ 10^9 per sec).
However, some energy levels in metals (and their ions) are split into 'sub-levels' or `fine structure states'. Downward transitions amongst these low-lying energy levels **can have a very low probability of occurring spontaneously** (typically ~10-100 per sec - or 1 per 0.01-0.1 sec). Because of this they are often also called METASTABLE states. **Photons emitted in this way result in what are called FORBIDDEN LINES.**
The formation process of these Forbidden Lines provides the cooling of the nebula gas in the following way:
(a) In the ISM, the atom density is too low for atom - atom collisions to occur. However atom-electron collisions do occur. Bound electrons in the lower levels, of e.g. O^+ and O^{++}, are excited to higher levels by COLLISIONS with free electrons in the gas, REMOVING some of the Kinetic Energy of the colliding electrons. These free electrons come from the photoionisation of H.
Excitation potentials of these fine structure levels are ~ 1 eV, which is approximately equal to the energy of the electrons (kT ~1 eV at T_e = 10 000 K). (Note: all levels of H and He have much higher excitation potentials, meaning they cannot be excited by collisions with electrons of the same temperature. *In realtà I livelli più alti del H sono vicini, ma la loro popolazione è pressochè nulla*).
(b) Fine structure states are metastable, so the electron sits there for a relatively long time (0.01 - 0.1 sec). Remember, collisions with atoms are negligible. This gives the electron the chance to RADIATIVELY de-excite by itself (spontaneously), thus emitting a forbidden line

photon. The energy is now transferred to the photon.

Note: if the gas density is too high, the jump to the lower level can be induced by another collision before spontaneous de-excitation has time to occur. This is called collisional deexcitation - no photon is emitted but kinetic energy is returned to the gas. For most HII regions the rate of radiative (spontaneous) de-excitation is greater that collisional de-excitation.

Every forbidden transition has a "critical density", above which the collisional de-excitation (by electron - atom collision) rate exceeds the radiative (spontaneous) de-excitation rate.

In these circumstances we say the forbidden line becomes “quenched".

Despite the low abundance of metals (compared to H), forbidden transitions make a significant contribution because their excitation potentials (1- few eV) are so low. Only electrons with thermal (energy ~ kT) energies are needed, rather than ionising photons (E > 13.6 eV).

(c) because the photon emitted in the Forbidden Line transition has only a very weakprobability of being absorbed the emitted photon easily escapes from the nebula gas, carrying away photon energy and this cools the gas.

By this process we have REMOVED kinetic energy from the gas and transformed this to photon energy which ESCAPES from the gas easily.

When this process is included in calculations of the heating and cooling rates it turns out that irrespective of the T_{eff} of the central OB star, we end up with electron temperatures of between 7000 - 10 000 K, as observed.

The term `forbidden' is really a misnomer! It was coined before we understood all the rules governing electron transitions. A more intuitive name for forbidden lines is “collisionally-excited lines" (CELs), since they are emitted following collisions of free electrons with ions in the nebular plasma.