Current and future development of the photoionization code Cloudy

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Outline

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Introduction

Modeling high-density gas – CRM models

- The H- and He-like iso sequences
- The Stout database

Time-dependent modeling

- Simple model of a recombining planetary nebula

Spinning dust

Brief outline of long-term plans

Introduction

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- The space between stars (galaxies) is filled with a very tenuous gas called the interstellar or intergalactic medium (ISM / IGM).
- This medium is usually irradiated by strongly diluted radiation fields and is therefore far removed from thermo-dynamic equilibrium. Other energy sources could be shocks, magnetic reconnection, cosmic rays, radioactive decay, etc.
- The gas may be ionized, neutral, or molecular and often also contains dust grains.
- The geometry of the gas is often complex, and as a result, radiative transfer is complex as well.

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- Often it can be assumed that the gas is in a steady-state equilibrium, but this is not always the case.
- To model the ISM / IGM a sophisticated numerical code is needed.
- For this purpose the open-source code Cloudy was created on 28 August 1978 at the IoA, Cambridge.
- The emphasis is on detailed treatment of microphysics, but it also needs simplifying assumptions: 1D spherical geometry with simplified RT (OTS, escape probs), no shocks, basic treatment of magnetic fields, no radioactive decay.

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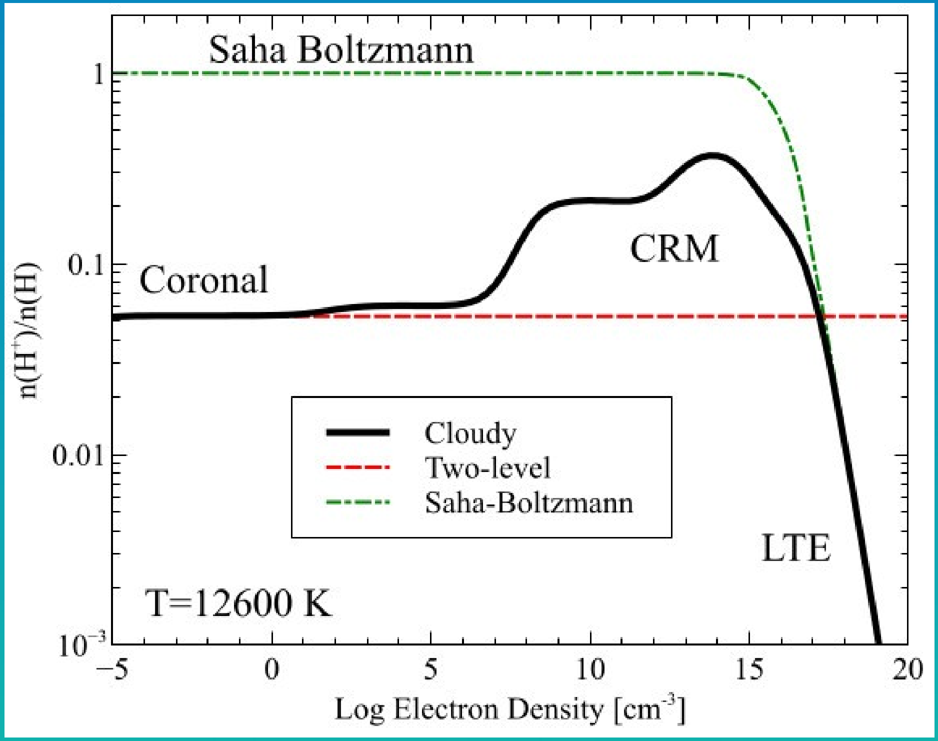
- The physics is continually being improved, with the aim of making the code suitable for the widest possible range of physical conditions (low to high density, X-ray plasmas to PDRs, purely collisional models, dusty plasmas, etc).
- The goal is to create models for the emitted spectrum as well as the physical conditions in the medium.
- It is the only code capable of creating a self-consistent model of the ionized and PDR regions surrounding an ionizing source. It has a full network to model the chemical reactions in the PDR.
- Other strong points are: realistic input spectra, sophisticated grain model, detailed microphysics.

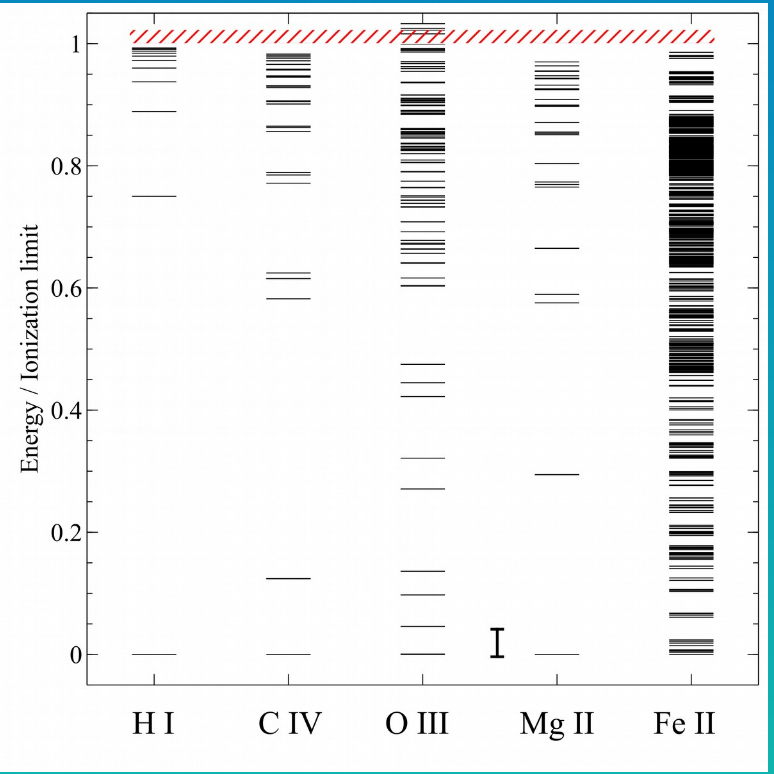
CRM regime

- Cloudy needs to be able to calculate the ionization balance over a wide range of densities.
- In the low density limit, the ionization balance can be derived using the two-level (aka coronal) approximation.
- In the high density limit, collisions will drive the gas into LTE.
- In between the behavior is complex and requires many levels.
- Cloudy needs large model atoms!



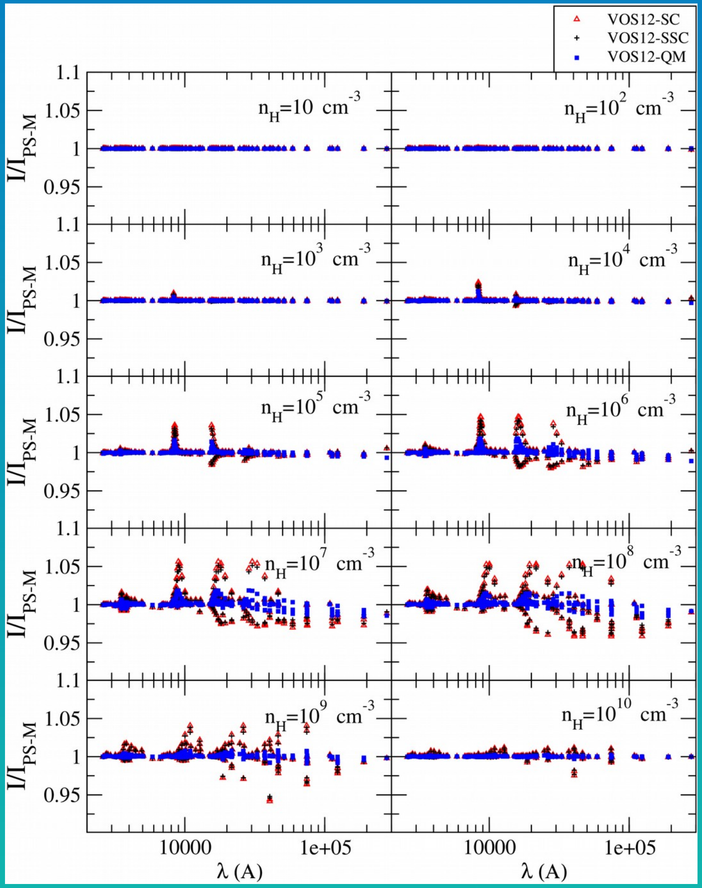
H- and He-like ions

- For H- and He-like ions, the first excited level is much closer to the ionization limit than the ground level.
- For these ions, collisional excitation is generally not important and recombination dominates.
- Excited levels couple to the next ionized state and not the ground state.
- You need many Rydberg states to model the ionization balance correctly.
- This is feasible due to regularities in the model atom.



H- and He-like ions

- Accurately modeling the He I spectrum is important for determining the primordial He abundance. Line strengths need to be determined to 1% accuracy.
- We reviewed our collisional data (Guzmán+ 2016, 2017, 2019) and changed Vrinceanu & Flannery (2001) → an improved version of Pengelly & Seaton (1964) for l-changing transitions.
- We are now discussing how to split up n-changing collional data.



H- and He-like ions

- Accurate predictions for the recombination spectrum require hundreds of levels to be modeled.
- Fully resolving all levels is computationally unfeasible.
- We are now implementing the matrix condensation technique to speed things up (Burgess & Summers 1969, Brocklehurst 1970).
- This will enable us to routinely create large model atoms and improve our predictions.
- However, refactoring of the code is needed. Several bugs were discovered in the process.

The Stout Database

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- For systems with more than two electrons, the situation is much more complex.
- Low-lying excited states usually exist → collisional excitation is important, which cools the gas.
- Simple extrapolations of atomic data do not work, and we must rely on laboratory work (energy levels) and large-scale computations (most other atomic data).
- This effort is ongoing and far from complete.
- Initially we relied on the Chianti database, but this has limitations (set up for Solar modeling).
- Hence we created our own Stout database.

The Stout Database

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- It is set up to store energy levels, transition probabilities (TP), and collision strengths (CS) for atomic and molecular species.
- It is still in development, and we currently use a mix of Chianti and Stout data.
- For many ions we only have "baseline" models: levels and TP data from NIST, but no CS data (which then defaults to g-bar data).
- We are now starting a major overhaul of the baseline models, using updated NIST level and TP data and combining this with open-ADAS CS data.
- Stout should become a standalone database.

Molecular data

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- We are in the process of updating the LAMDA database to the latest version. This contains data for NLTE modeling of molecular lines.
- We will also be adding ro-vibrational collisional data for CO and SiO (and isotopologues) provided by Ziwei Zhang. These are the first molecules where vibrationally excited states are modeled!
- We are furthermore in the process of updating our chemistry network to the UMIST RATE2012 release. Here we saw in some cases exponential runaway in the solution, and it is not clear yet how we should tackle this.
- For neither update it is clear whether it will be in the next major release.

Time dependent models

- Cloudy has an experimental mode to generate models of hydrodynamic flows.
- This mode can also be used to create time-dependent models.
- Here we will show a first application to a planetary nebula that is on the cooling track.
- We assumed a central star with a fixed temperature of 200 kK and varying luminosity starting at 10^4 Lsol.
- The nebula has a constant density of 10^3 cm^{-3}, with an inner radius of 3.16×10^{17} cm and an outer radius of 8.32×10^{17} cm. It contains graphite grains.

Time dependent models

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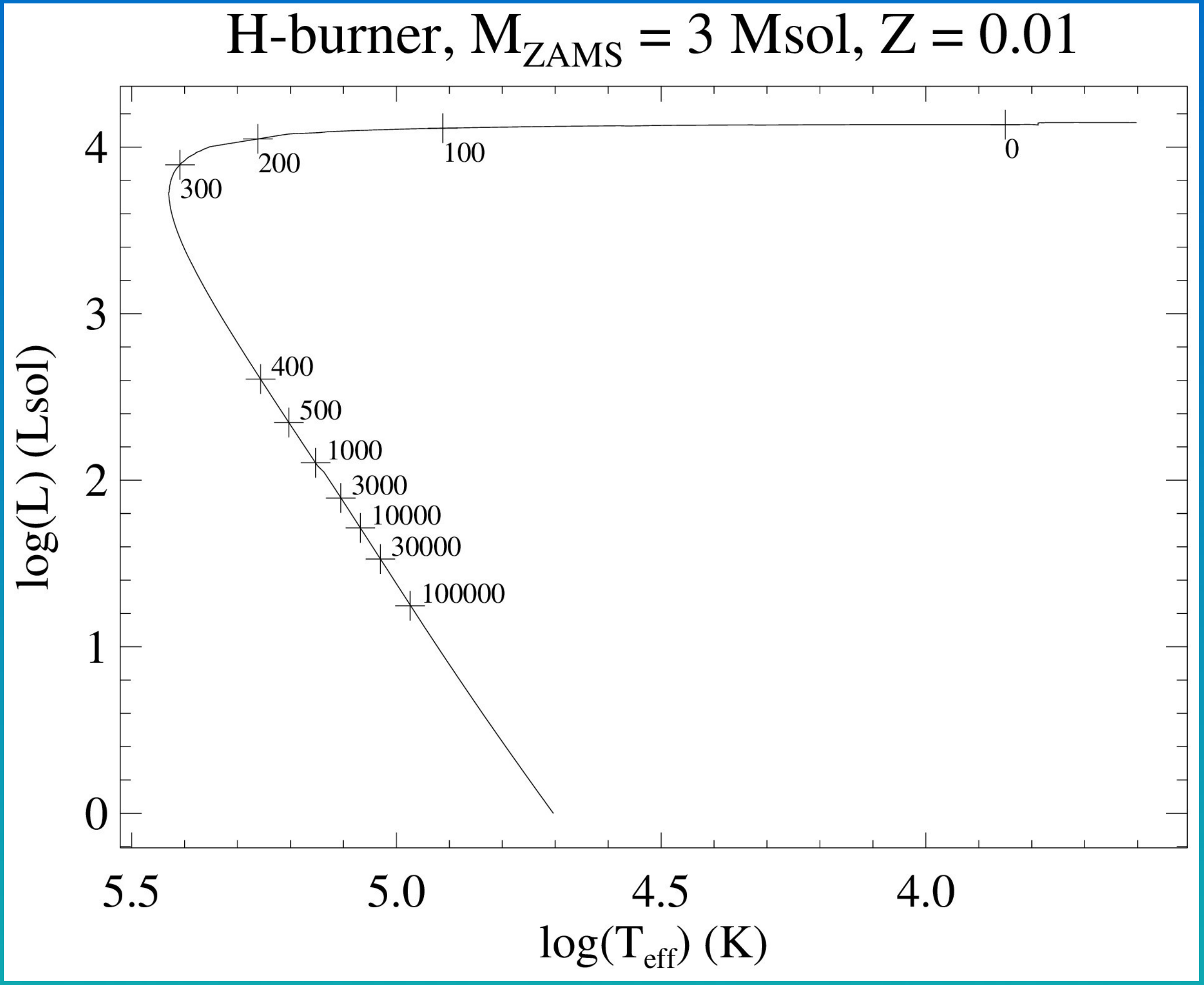

Track taken from Miller Bertolami, 2016, A&A, 588, A25

Time dependent models

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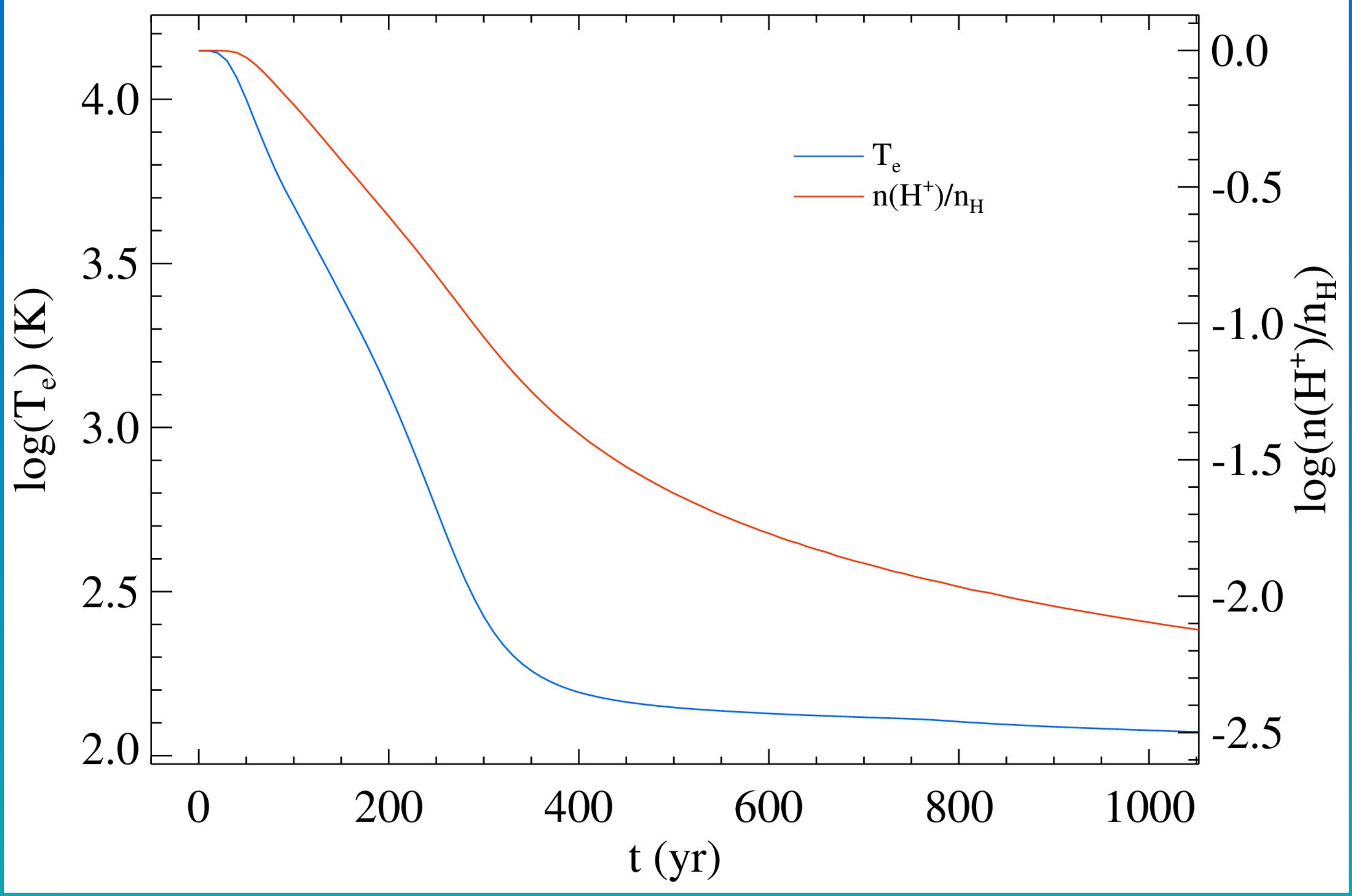
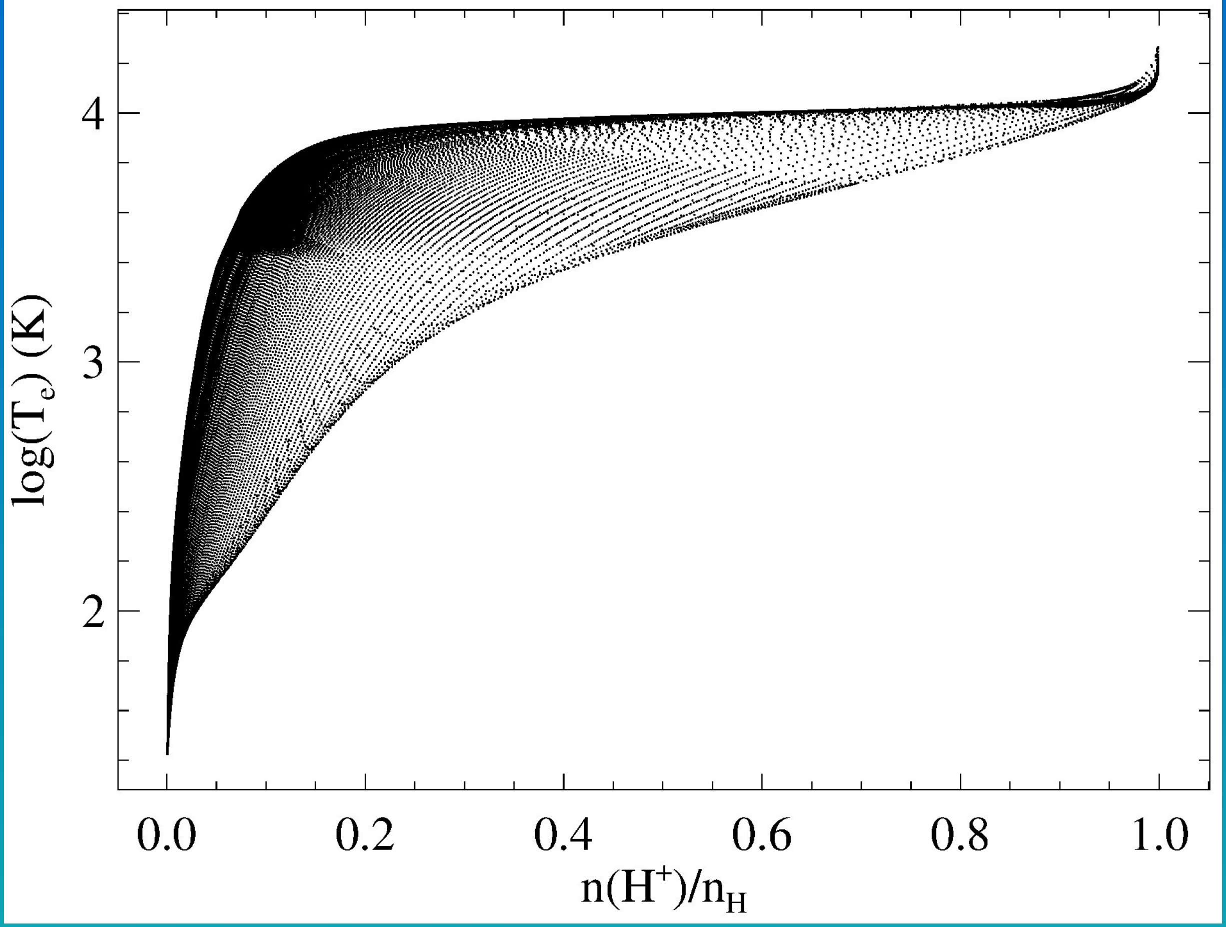


The evolution with time of T_e and $n(H^+)/n(H)$ at a depth of 2×10^{17} cm.

Time dependent models



T_e vs. $n(H^+)/n(H)$ at any depth in the cloud. For 50% ionization Te can be as low as 3370 K, and for 10% ionization even as low as 242 K!

Time dependent models

- Several evolved PNe show so-called cometary knots.
- These are high-density molecular condensations embedded in ionized gas.
- The origin is still debated.
- In van Hoof+ (2010) we argued that an instability in recombining gas could be the origin.
- This simulation shows that recombination is very fast and thus still a plausible source for the knots.

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Spinning dust

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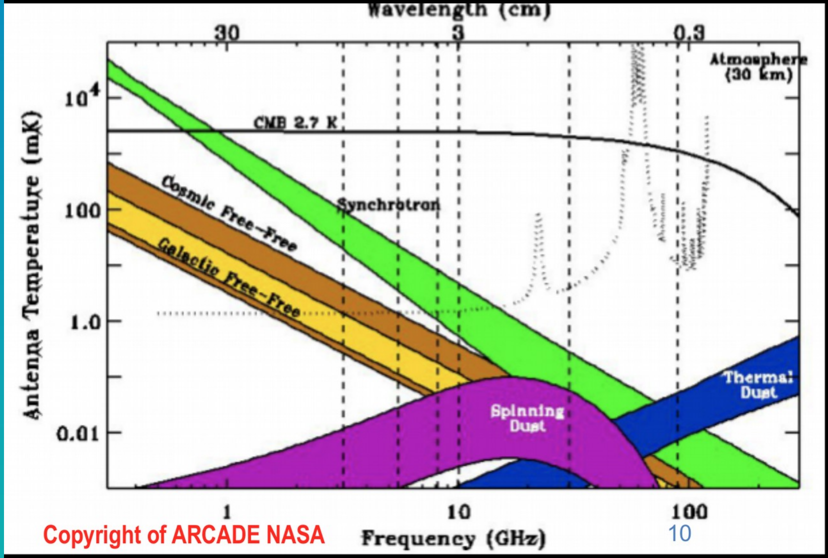
- If the grain has a dipole moment, the spinning grain will emit (anomalous) dipole radiation. Peaks typically at 20-30 GHz.
- The power depends strongly on grain size → only very small grains are important.

Small grains are better emitters:

$P \sim \omega^4$ $\quad \omega \sim r^{-5/2}$ $\quad P \sim r^{-10}$

- Initially it was thought that PAHs were the source, but now nano-diamonds look like a better candidate.

Spinning dust, i.e. spinning tiny PAHs with dipole moments, has become an accepted foreground



Long-term development

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- The long-term goal is to make Cloudy suitable for every environment. For that significant infrastructure still needs to be developed.
- Shocks. A proposal to implement shocks in Cloudy has recently been accepted, so in the coming years this should be implemented.
- Exact RT. Initiatives have been taken to implement this, but so far no code has been created.
- Integration in hydro codes. We need a simplified version of Cloudy that is much faster.
- 3D RT? There are competing codes that implement this (Mocassin). For now we have Cloudy-3D which is a pseudo-3D implementation based on Cloudy.

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Cloudy is freely available on this website:

https://wiki.nublado.org/

We also organize workshops around the world:

2012 Lexington, 2014 Queen's University Belfast, 2014 Leiden Observatory, 2015 Queen's University Belfast, 2015 Durham, 2015 Warsaw, 2015 Pune, 2016 Shangdong, 2017 Tonantzintla

Additional stops: 2017 Belfast, 2018 Chiang Mai, 2019 Lexington