(Radio) ***Recombination lines (RRLs)***

Divakara Mayya (INAOE)

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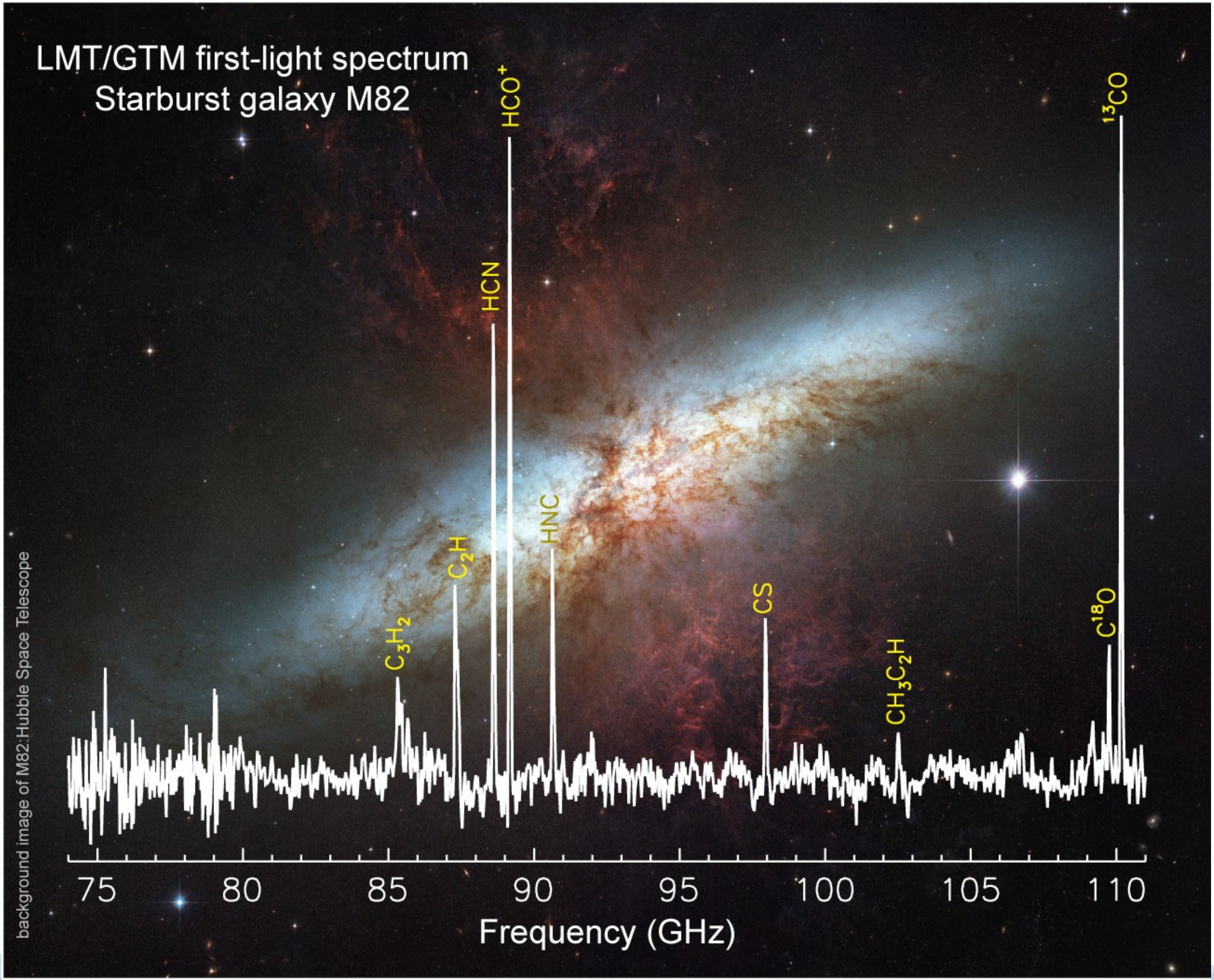
1. Why discuss atomic lines in a molecular astrophysics workshop?

Molecular lines and RRLs are linked through:

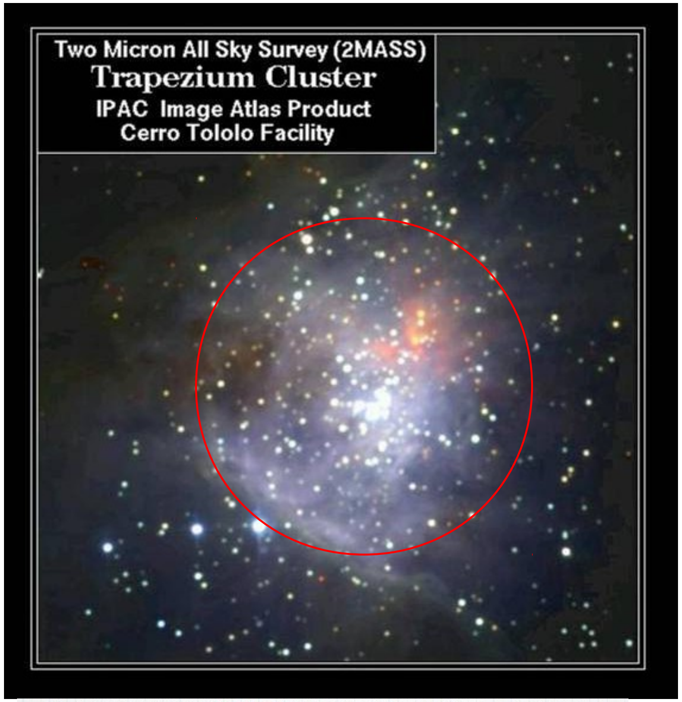
- **Star formation**
  - **MCs**
  - **HII regions**
- **MM Observations**
  - **molecular lines**
  - **MM RRLs**

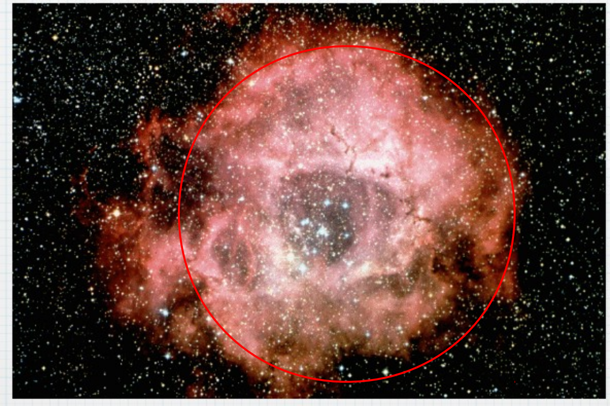
1.1 LMT/RSR spectrum of the starburst nucleus of M82

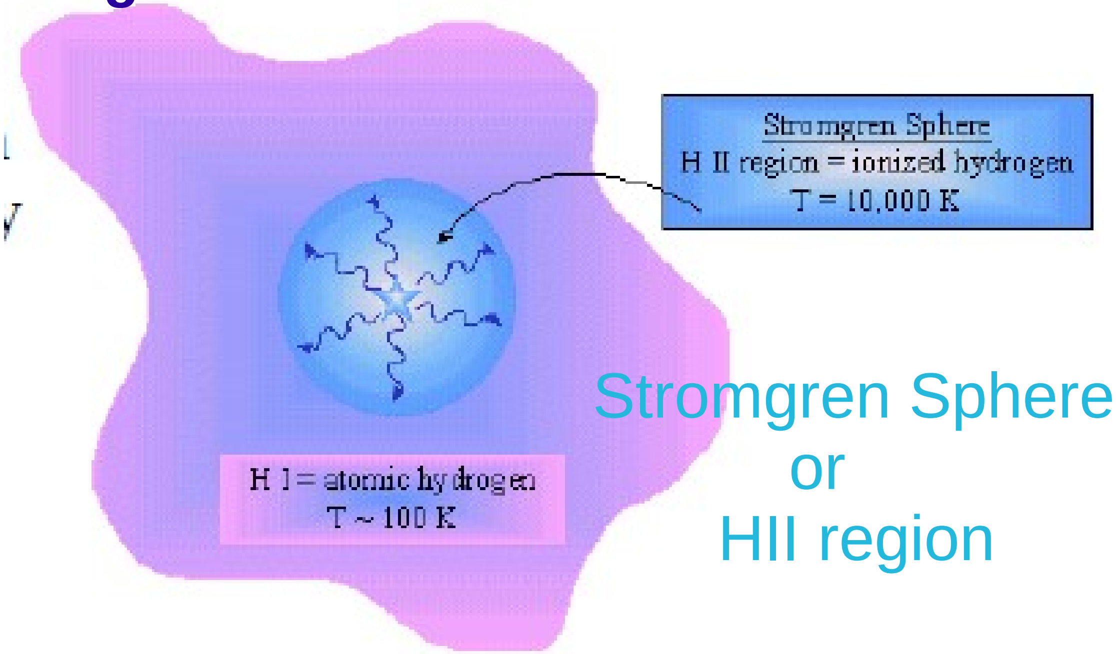


2. HII regions and recombination lines

Ionization of a Pure Hydrogen Cloud



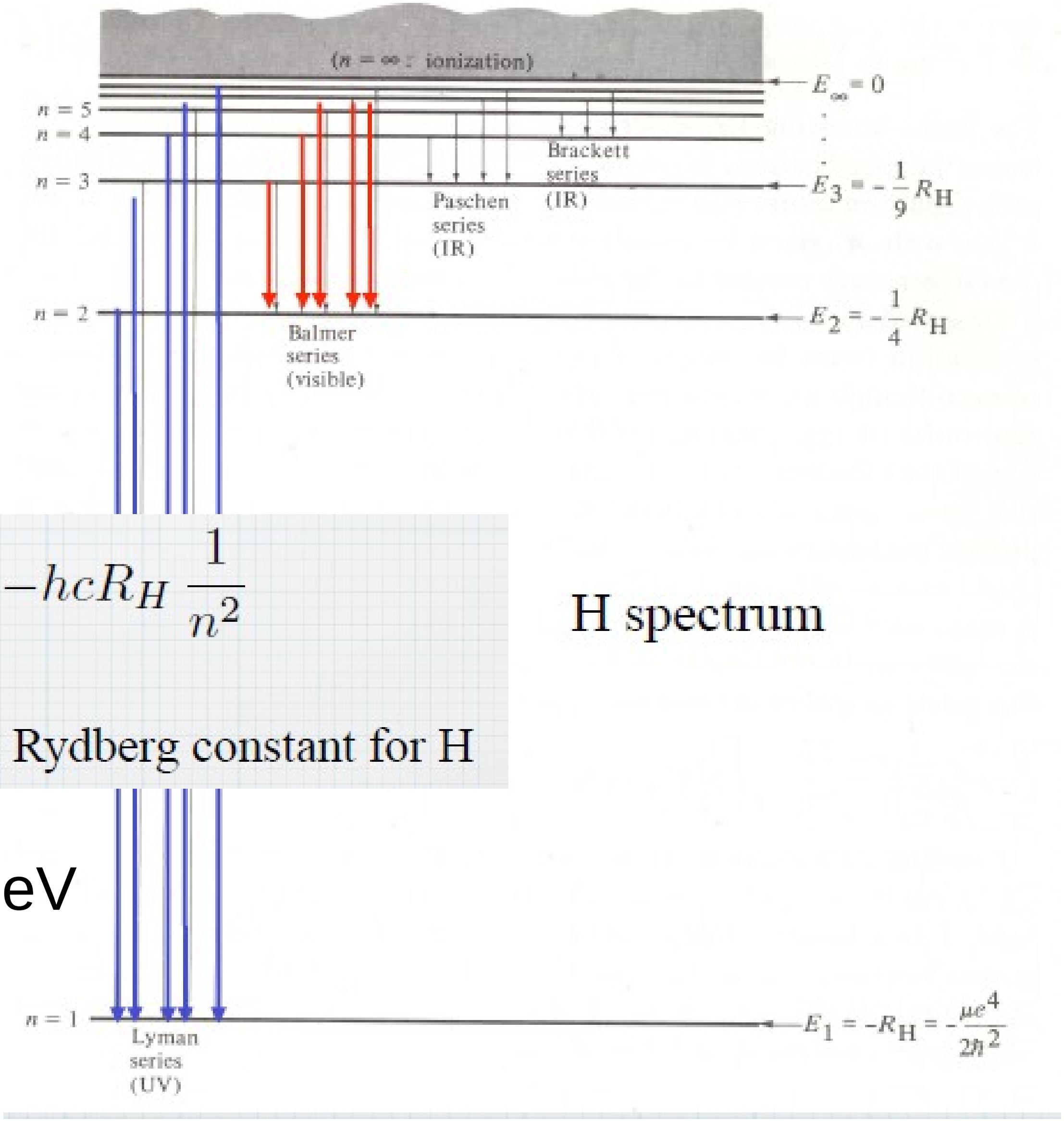




Stromgren Sphere
or
HII region

# of photoionizations/s
=
# of recombinations/s

2.1 Atomic Structure of a Hydrogen Atom



$$E = -\frac{\mu e^4}{2\hbar^2}\frac{1}{n^2} \equiv -hcR_H\frac{1}{n^2}$$

with R_H=109,677.585 cm^{-1} : Rydberg constant for H

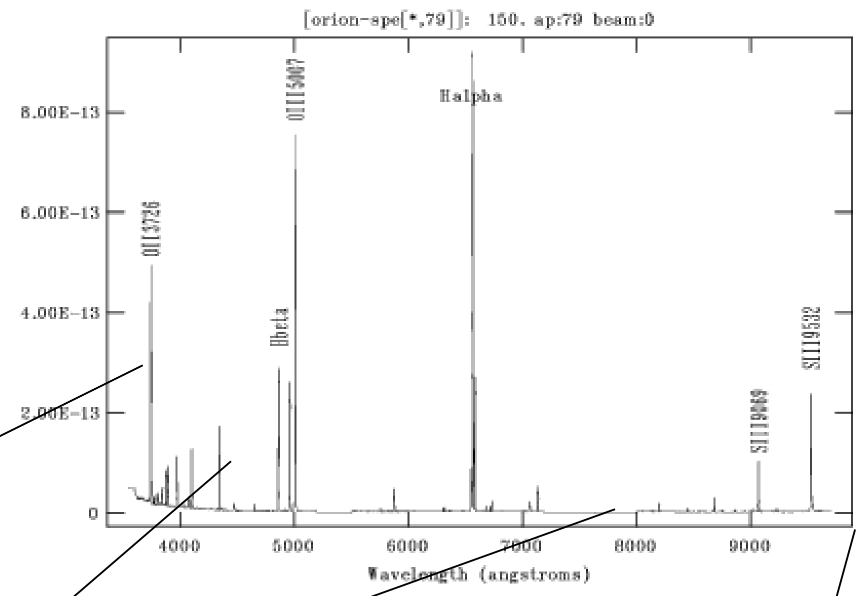
H spectrum

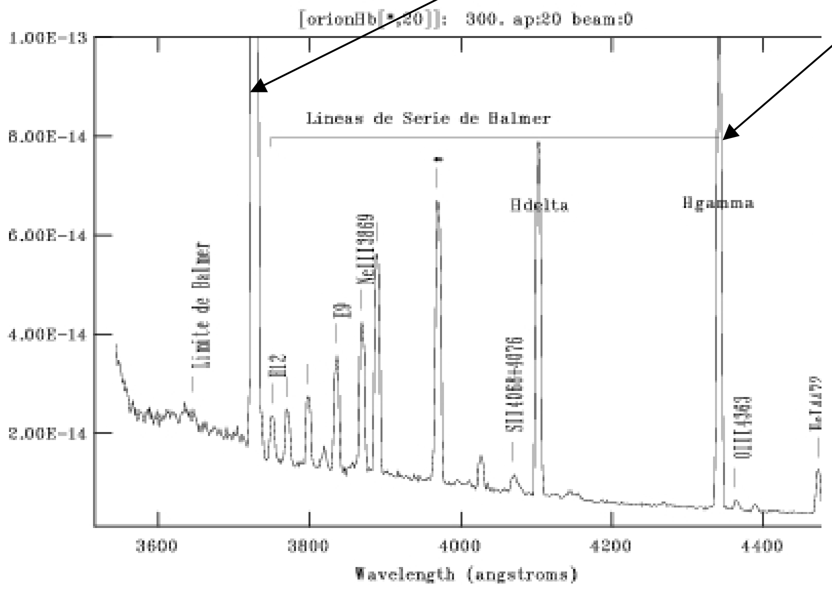
E (ionization) = 13.6 eV

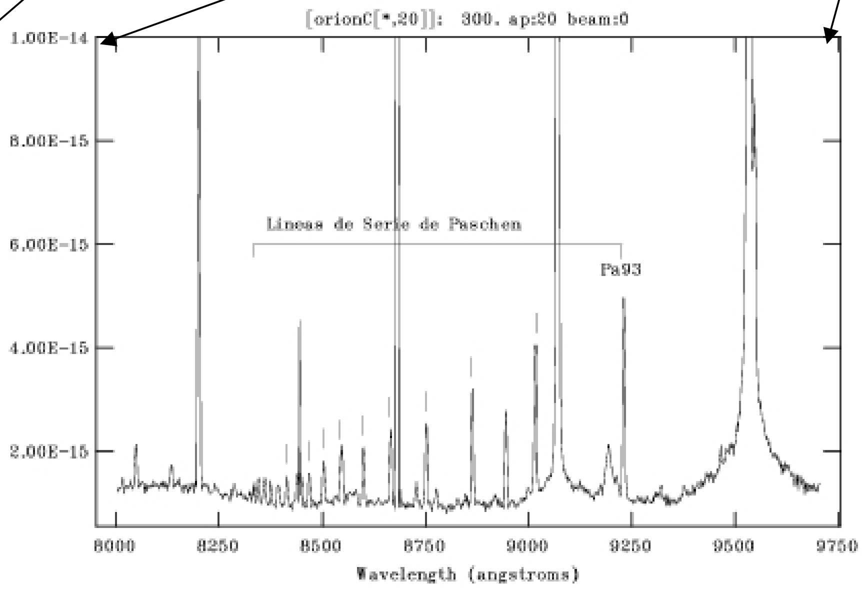
Wavelengths of important H Lines

- Lyα: λ_{vac}= 1215.68 Å (space UV)
- Hα: λ_{air}= 6562.73 Å (red) 3-2
- Hβ: λ_{air}= 4861.33 Å (blue) 4-2
- Hγ: λ_{air}= 4340.47 Å (blue) 5-2
- Hδ: λ_{air}= 4101.47 Å (violet) 6-2
- Paα: λ_{air}= 1.875 μm (poor transmission)
- Brα: λ_{air}= 4.051 μm (difficult)
- Brγ: λ_{air}= 2.166 μm (in infrared K band)

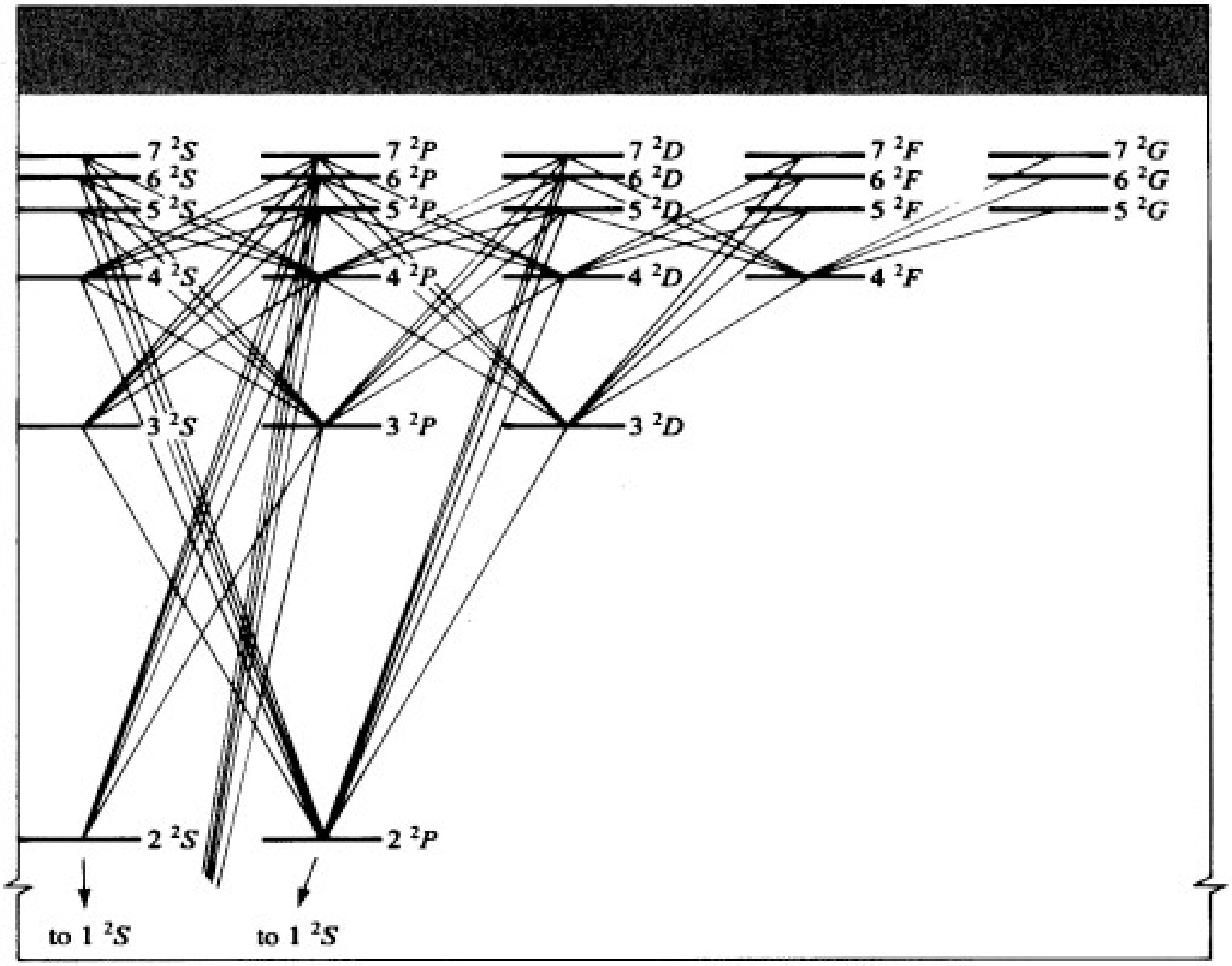
Balmer





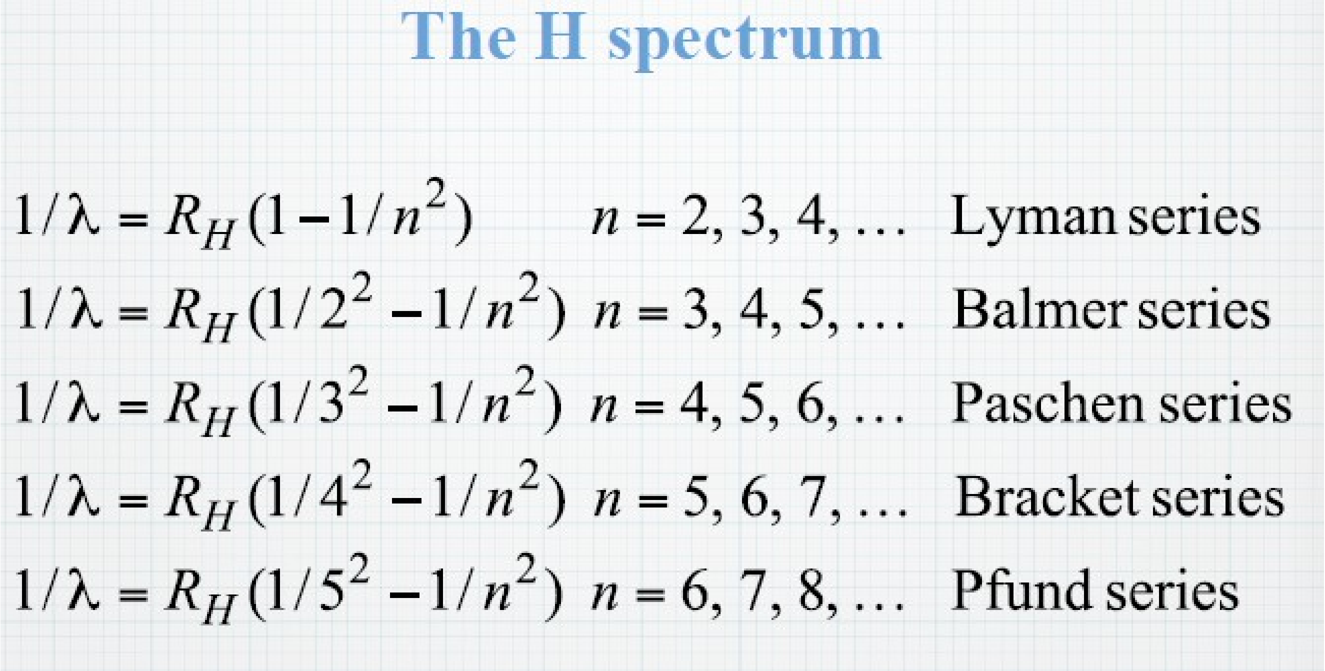


H spectrum: permitted transitions



3. Transitions between higher quantum levels: Calculated frequencies

Bohr 1913



The H spectrum

$1/\lambda = R_H(1-1/n^2)$	$n = 2, 3, 4, \ldots$	Lyman series
$1/\lambda = R_H(1/2^2-1/n^2)$	$n = 3, 4, 5, \ldots$	Balmer series
$1/\lambda = R_H(1/3^2-1/n^2)$	$n = 4, 5, 6, \ldots$	Paschen series
$1/\lambda = R_H(1/4^2-1/n^2)$	$n = 5, 6, 7, \ldots$	Bracket series
$1/\lambda = R_H(1/5^2-1/n^2)$	$n = 6, 7, 8, \ldots$	Pfund series

Brackett α line (**H4α**) at 4.05 μm (Brackett 1922)

Pfund α line (**H5α**) at 7.46 μm (Pfund 1924)

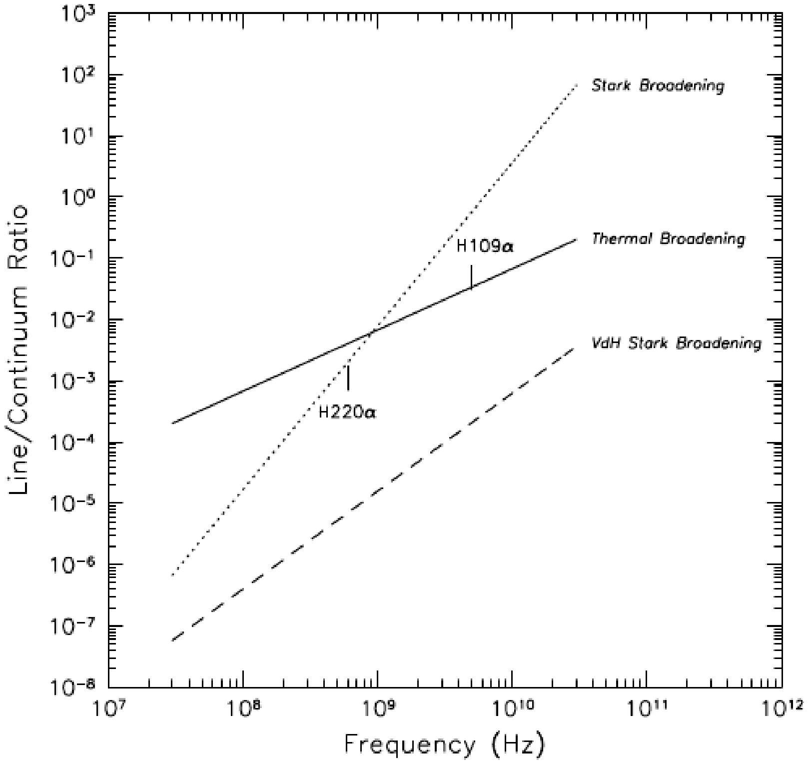
Humphreys α line (**H6α**) at 12.3 μm (Humphreys 1953)

H*nα* line ===> transition from ***n+1*** to ***n***

Hnβ *line ===> transition from* ***n+2*** *to* ***n***

Are there trasitions invloving higher n?

3.1 Transitions between higher quantum levels: Effect of Stark broadening



van de Hulst 1945

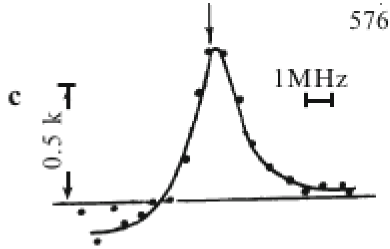
RRLs are too weak to be detectable at all radio frequencies

Kardashev 1959

Stark broadening

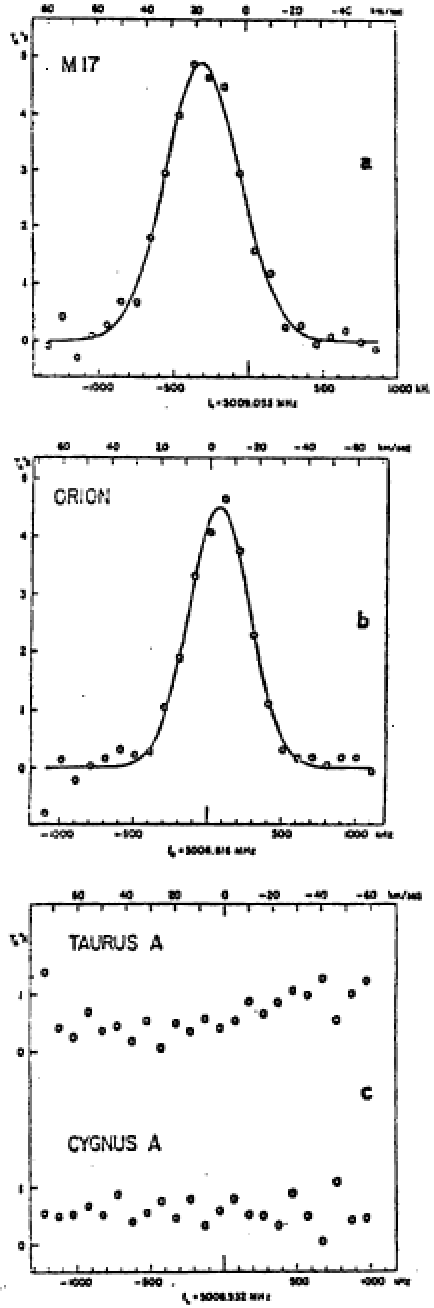
negligible for **ν** > 10 GHz

> **Δν(thermal)**, but **detectable** even at lower frequencies



Detection of **H90α** at 8.8 GHz by **Sorochenko & Borodzich (1965)**

3.2 Transitions from higher quantum levels: H109ɑ detection



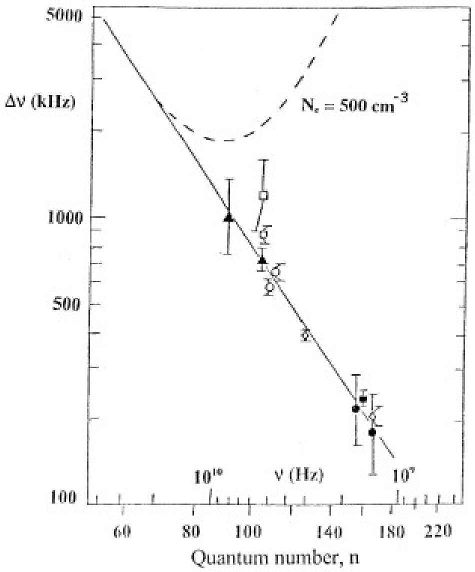
Hoglund & Mezger 1965

using 43-m NRAO Green Bank telescope

Many other studies conclusively detected RRLs from a number of *n* levels

e.g. **H253ɑ** at 400 MHz by
Pefield, Palmer and Zuckerman (1967)

3.3 Transitions between higher quantum levels: Understanding Stark broadening through astrophysics



The observed line widths up to n=166 suggested
Thermal, rather than, Stark broadening!!!

Does Stark broadening exist in astrophysical plasmas?

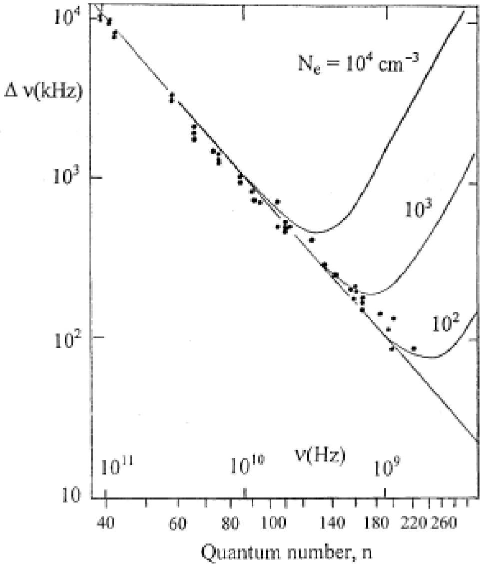
- Improved theoretical calculations explained the observed trend.
- However, theoretical densities < inferred densities from optical lines.

===>

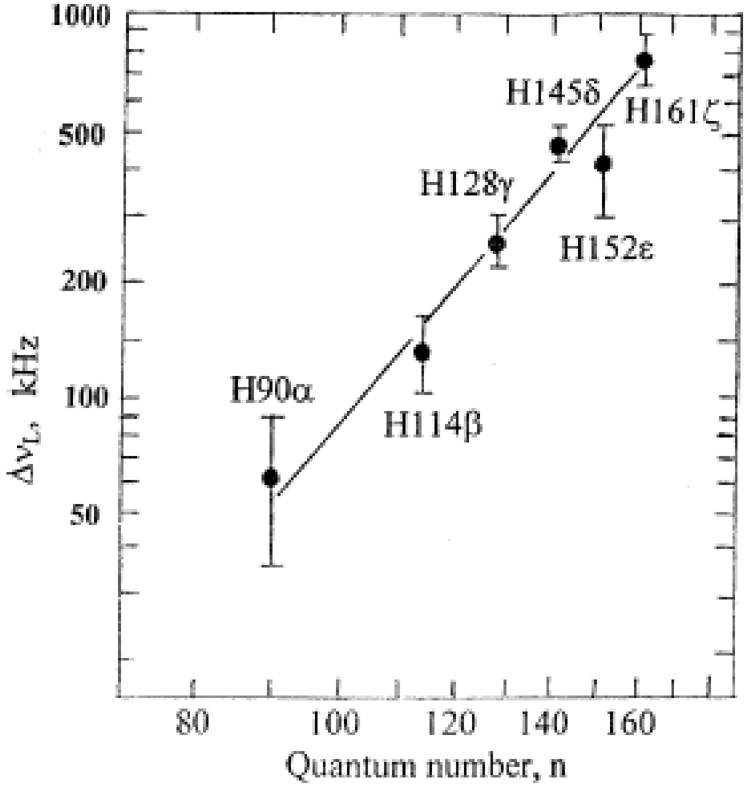
1. Density is not uniform in HII regions
2. high density gas that produces stark broadening doesn't contribute to the Line profile

Because: high n lines are at low frequency===> **Opaque**

3. Require beam-matched observations



3.4 Transitions between higher quantum levels: Understanding Stark broadening through astrophysics



Beam-matched observations
At 9 and 36.5 GHz by Smirnov et al. (1984)
Established the existence and the correct
Theoretical framework of Stark broadening

$$\Delta\nu_L^e = 8.2 N_e \left(\frac{n}{100}\right)^\gamma \left(1+\frac{\gamma}{2}\frac{\Delta n}{n}\right).$$

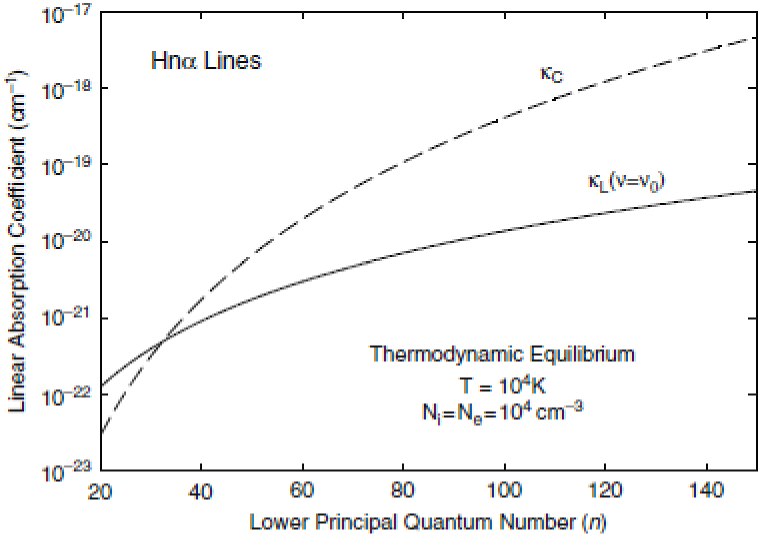
- **Inelastic** (n-changing) **electron collisions** are the principal contributor of Stark broadening in astrophysical Plasmas with **γ~4**

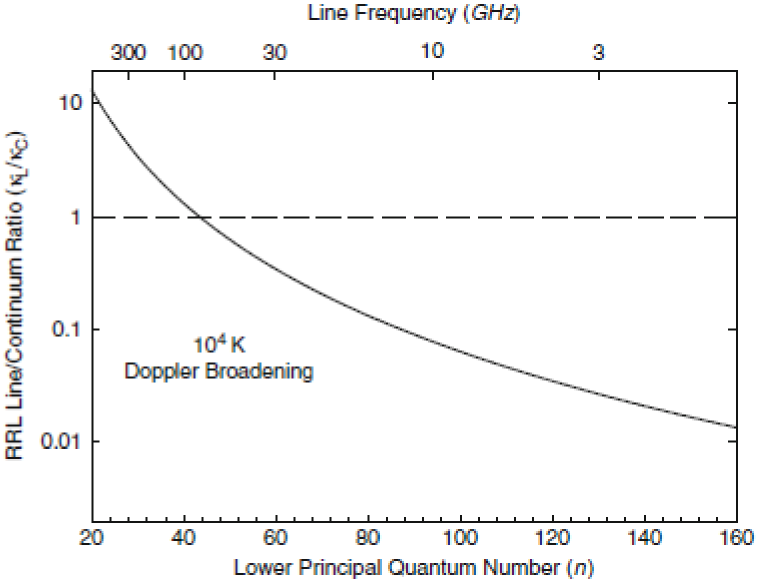
- i.e. ion collisions and elastic (l-changing) collisions don't contribute significantly.

- Impact approximation (interaction duration << the Time between interactions) is adequate for astrophysical plasmas.

4. Calculations of RRL line intensities (LTE)

$$\int_{\text{line}} \frac{I_L}{I_C}\,d\nu \approx 1.301\times 10^5\,\Delta n \frac{f_{n_1 n_2}}{n_1}\frac{\nu^{2.1}}{T^{1.15}}\,F\,\exp\left(\frac{1.579\times 10^5}{n_1^2 T}\right).$$



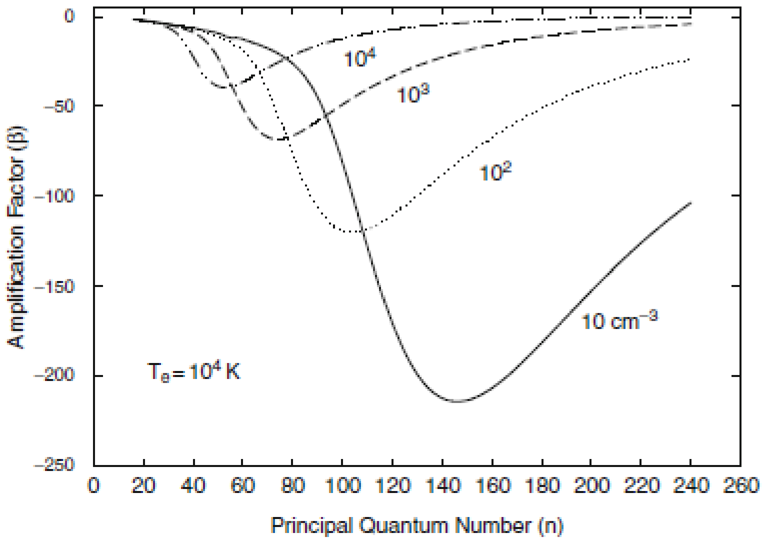


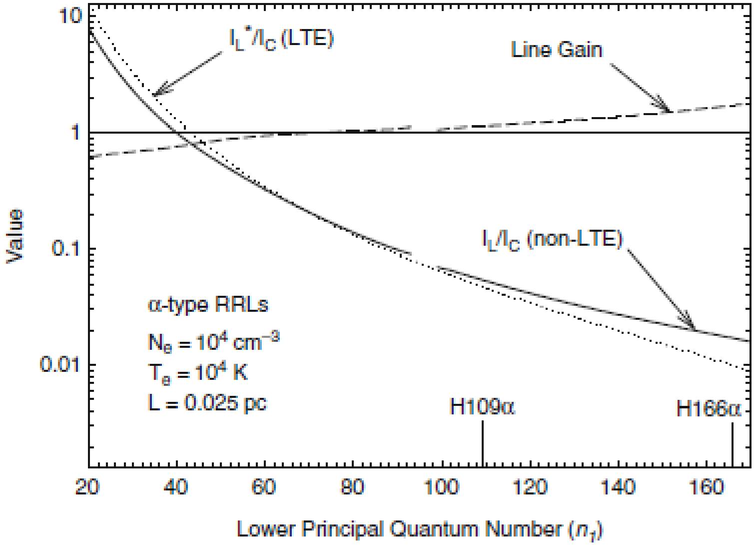
Line strength exceeds the continuum emission for n < 43 (ν>79 GHz)
===> Relatively easy to detect at mm wavelengths

4.1 Calculations of RRL line intensities (non-LTE): Line amplification

Where **β=** $b_{n_1}\left(1 - \frac{kT_e}{h\nu}\frac{d\ln b_{n_2}}{dn}\Delta n\right)$

K_L (non-LTE) = K_L(LTE)*β





At large densities, greatest amplification occurs for mm-RRLs

4.1 Calculations of RRL line intensities (non-LTE): Line amplification

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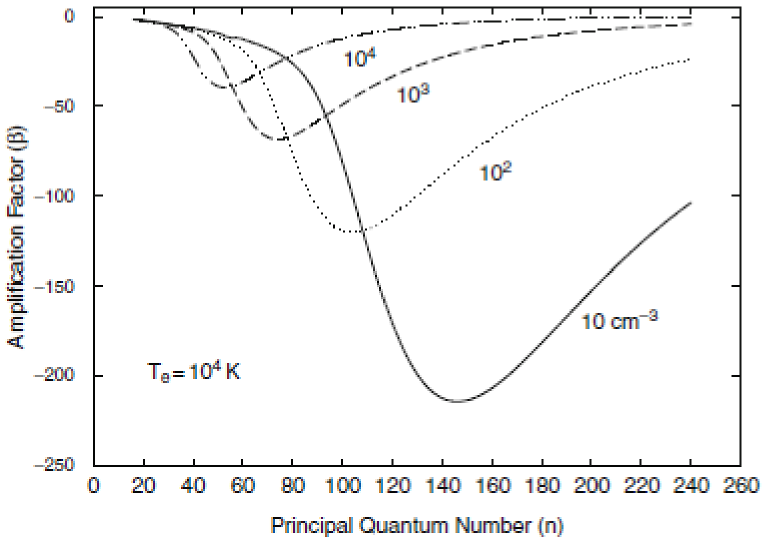
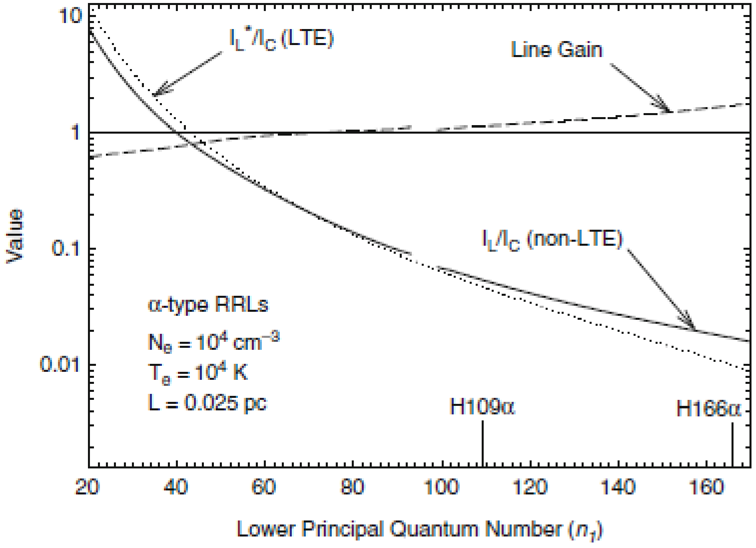
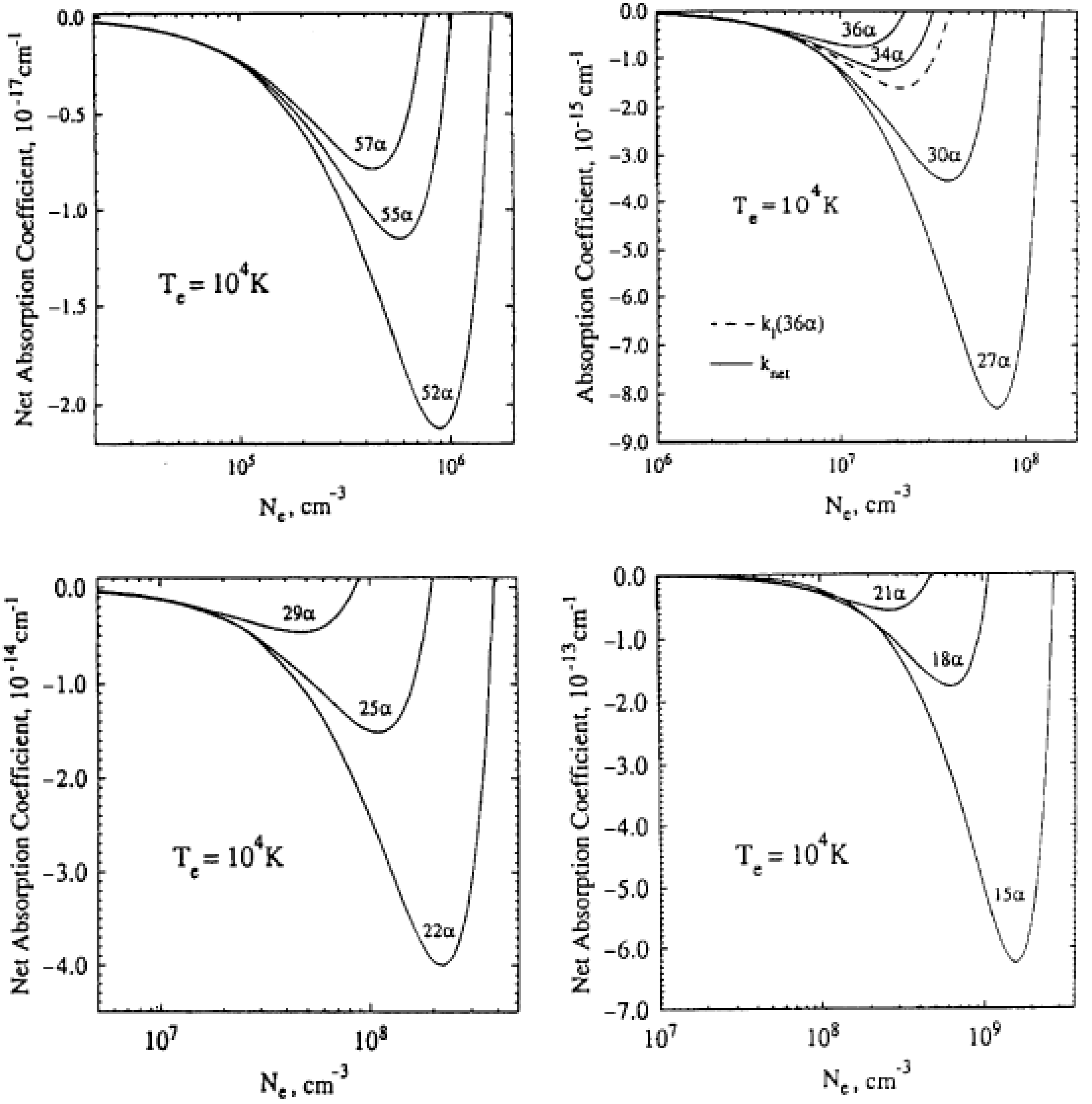




At large densities, greatest amplification occurs for mm-RRLs

4.2 Calculations of RRL line intensities (non-LTE):maser

$\beta << 0$ and $\tau_\nu = \tau_c + \tau_L < 0$

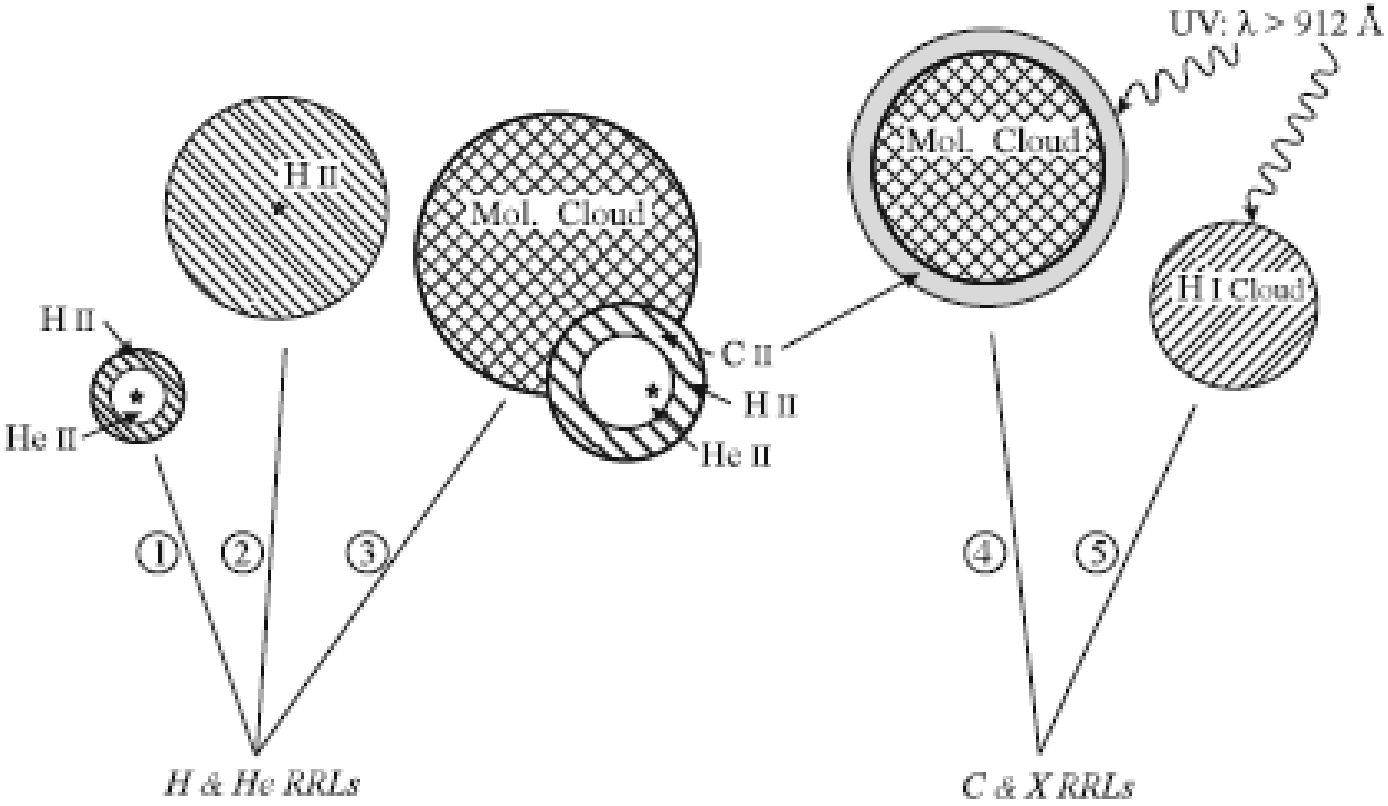


For each group of lines, there exists a narrow range of densities, where the maser gain is maximum

- Observed in MWC349 and η Carina

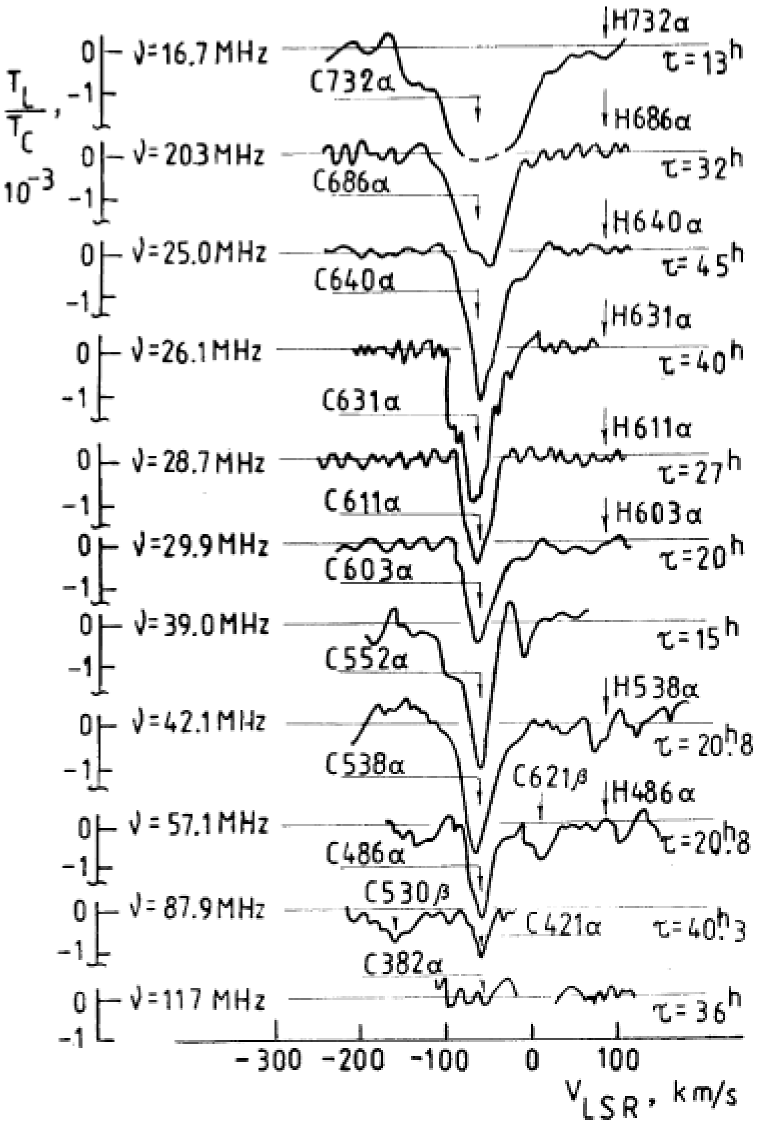
- Difficult to satisfy phase coherence over large emitting regions

5. Other regions from where RRLs can originate



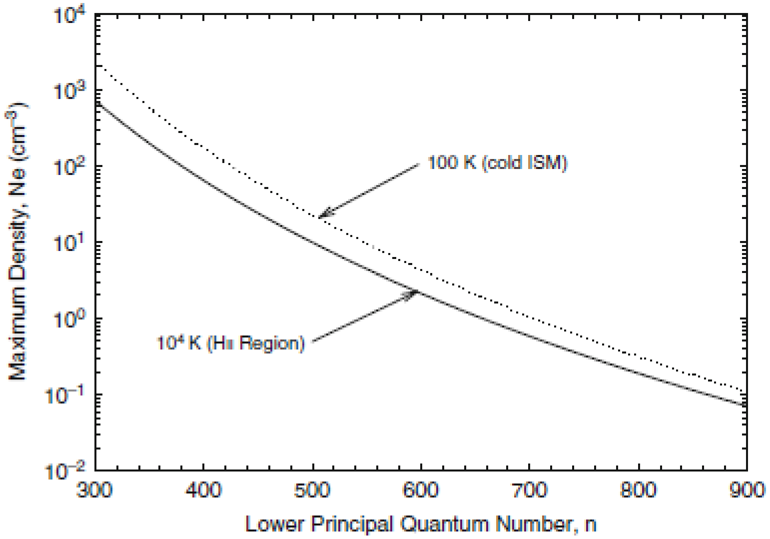
1 & 2 High and low density HII regions
3. CII region at the interface between HII and MC
4. CII region at the boundary of MC and diffuse ISM
5. CII region within HI clouds

5.1 Carbon RRLs



Sorochenko & Smirnov 1990

Why high-n CII lines are detected, but not high-n (n>300) H lines?



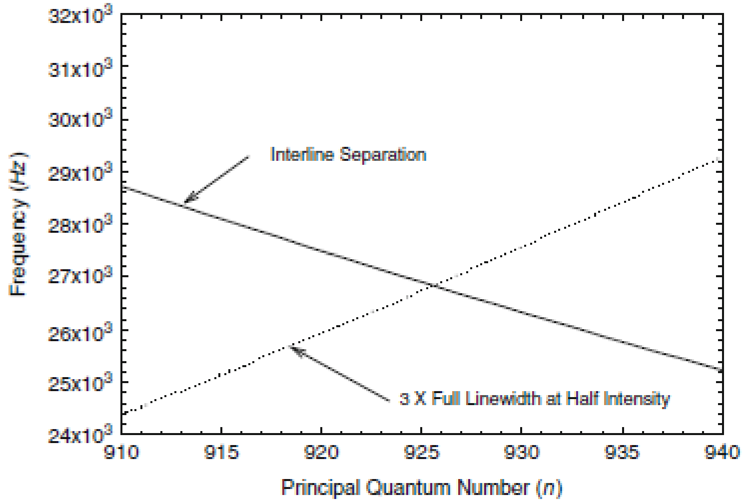
- Stark broadening
  - at high-n

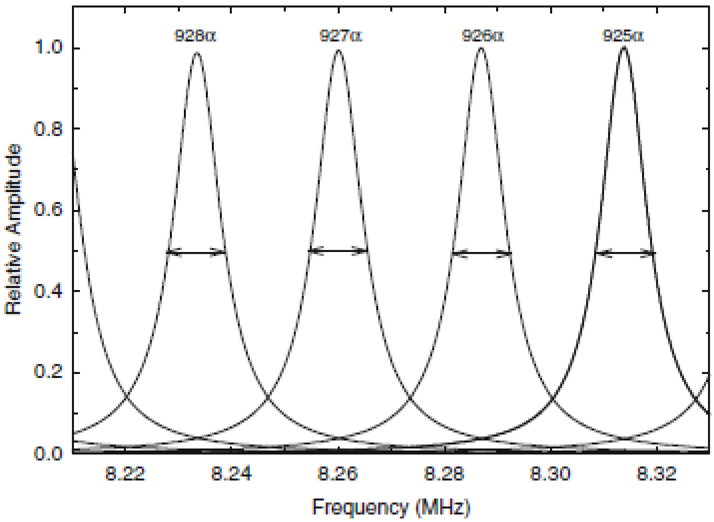
  ν(n2) – ν(n1) ~ $\Delta\nu$(Stark)
  - $\Delta\nu$(Stark) increases with densities

  ===> low-density cold ionized regions are required for high-n RRLs

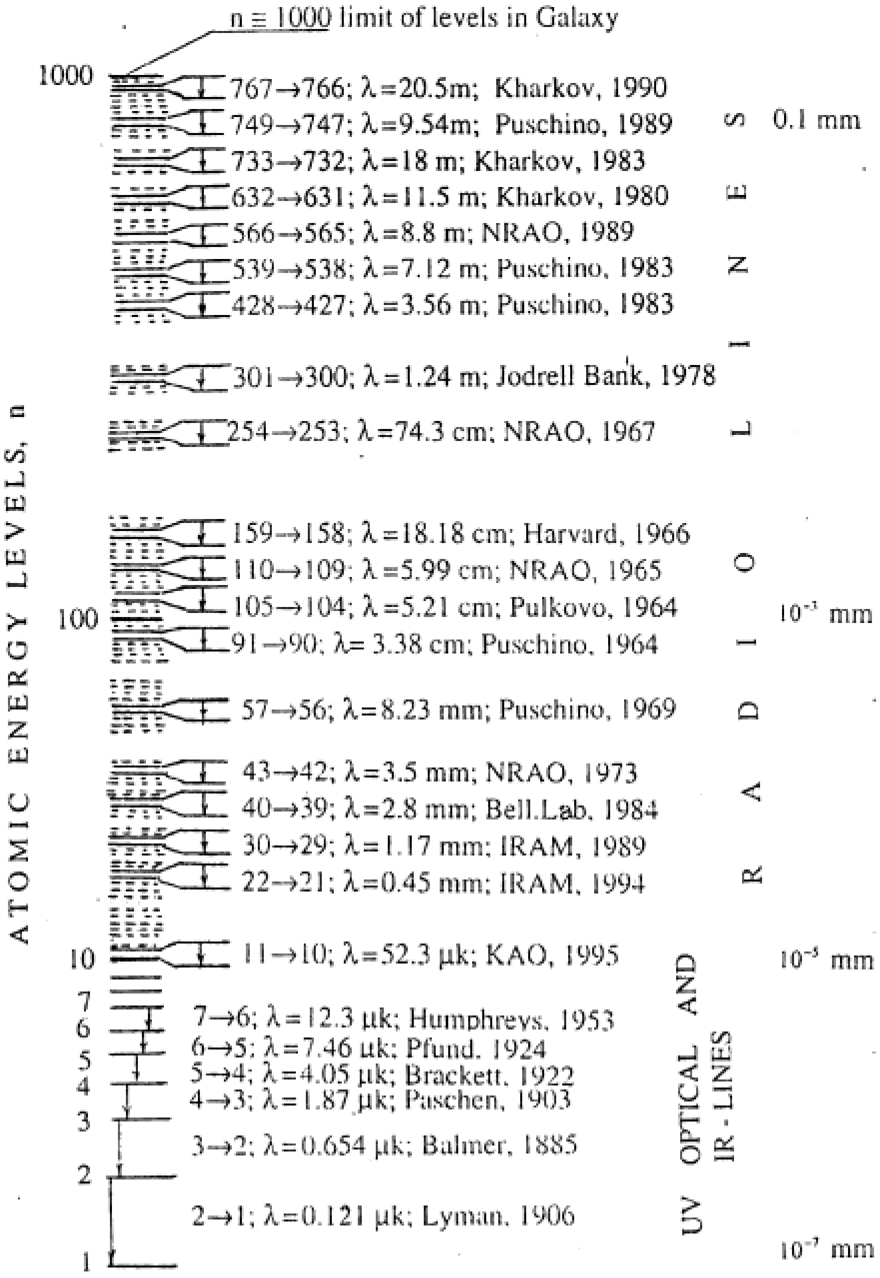
Ionized C present in diffuse, cold ISM
But not ionized Hydrogen

6. Existence and detectability of the high quantum numbers



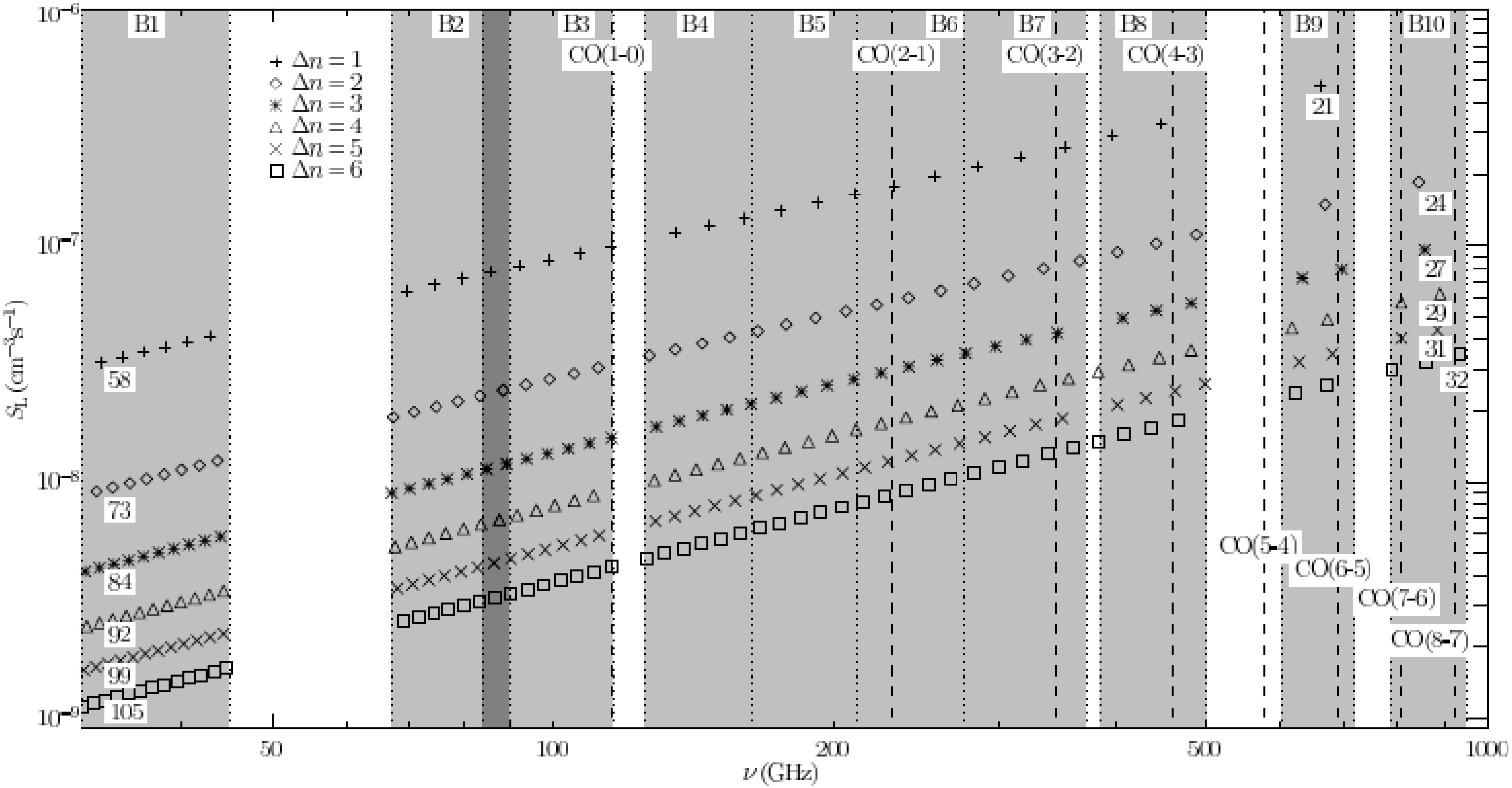


N=926 seems to be the limiting n value



7. Astrophysics using mm-wave RRLs

ALMA & EVLA **Peters et al. 2012**



8. RRLs from external galaxies

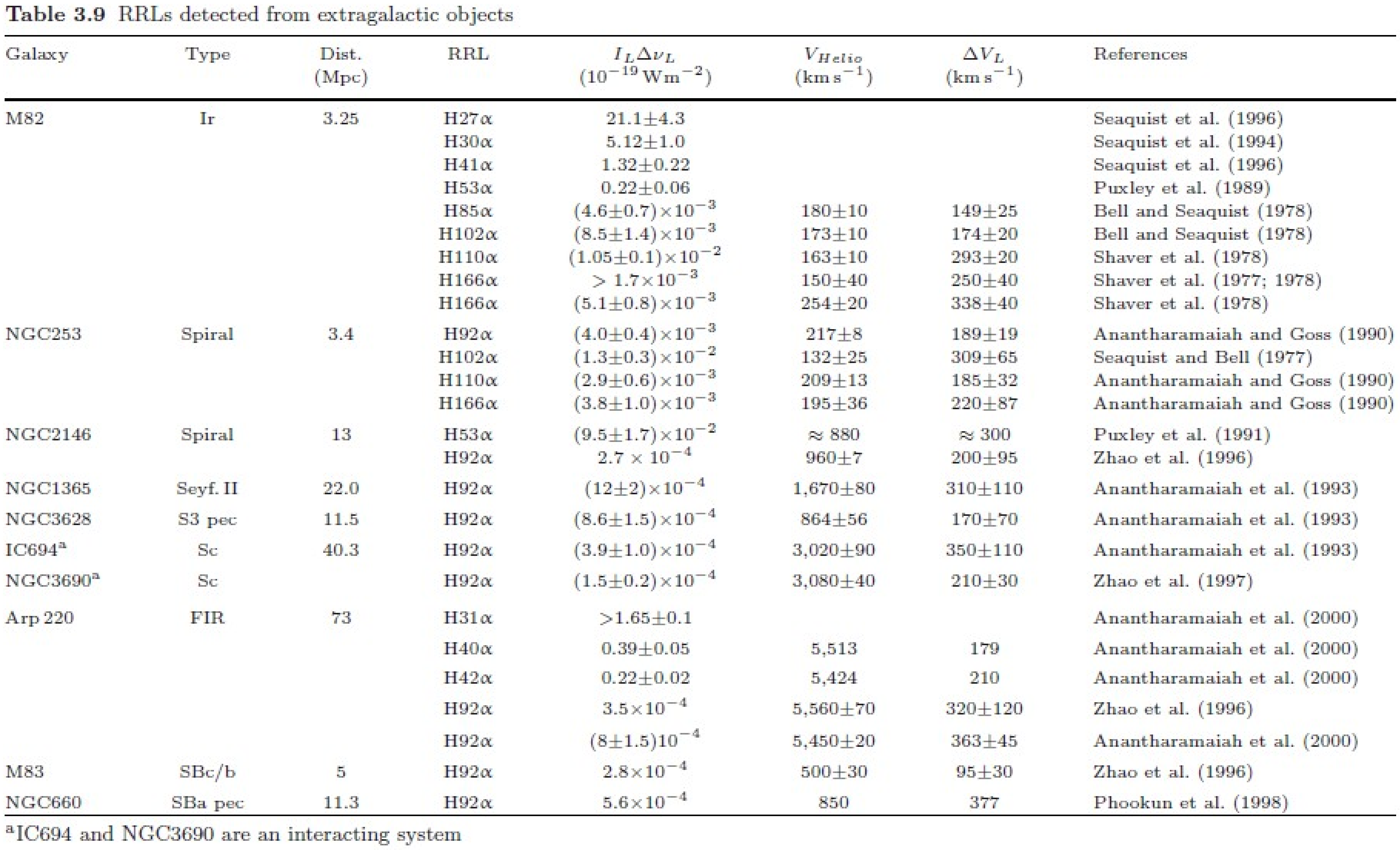
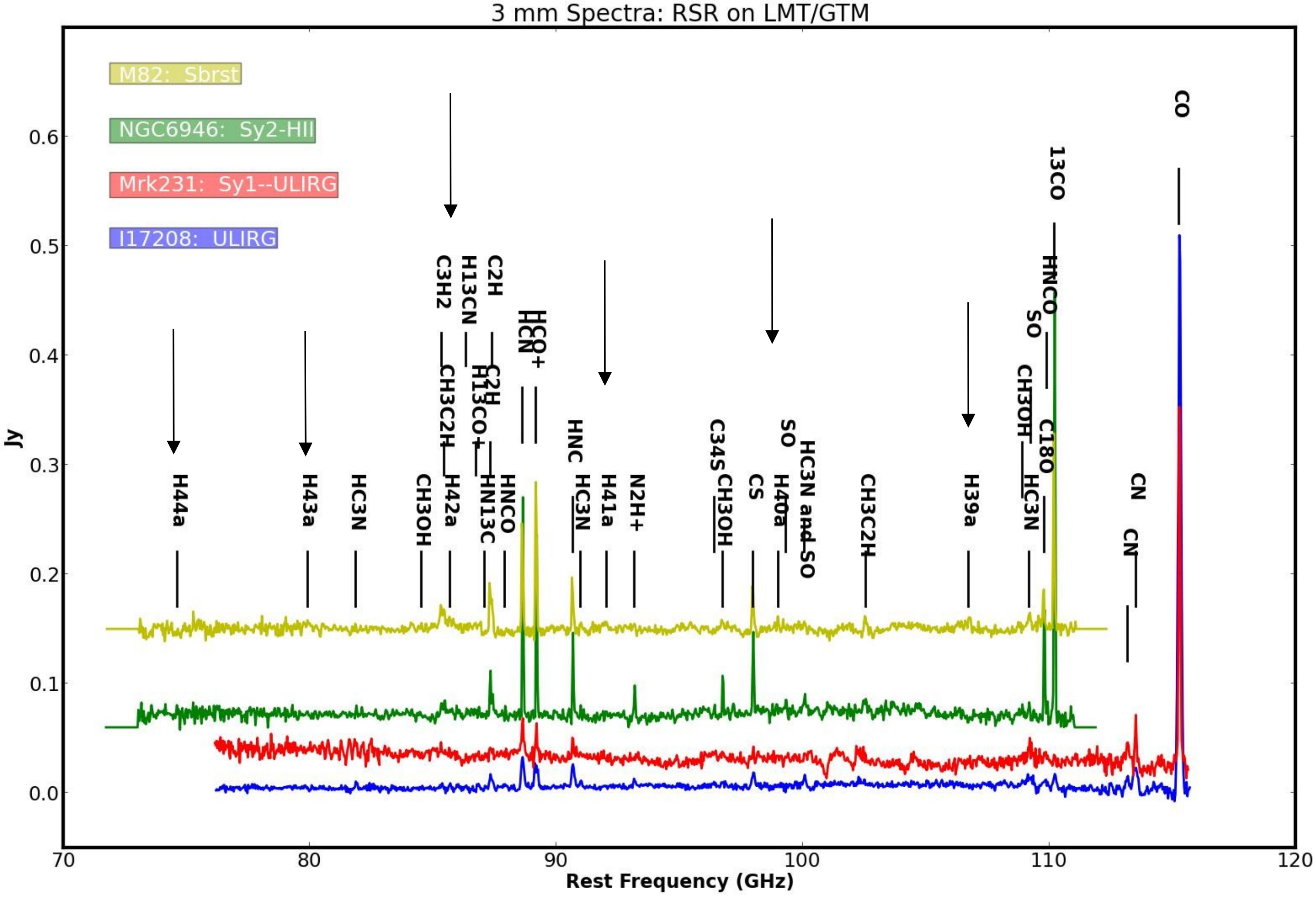


Table 3.9 RRLs detected from extragalactic objects

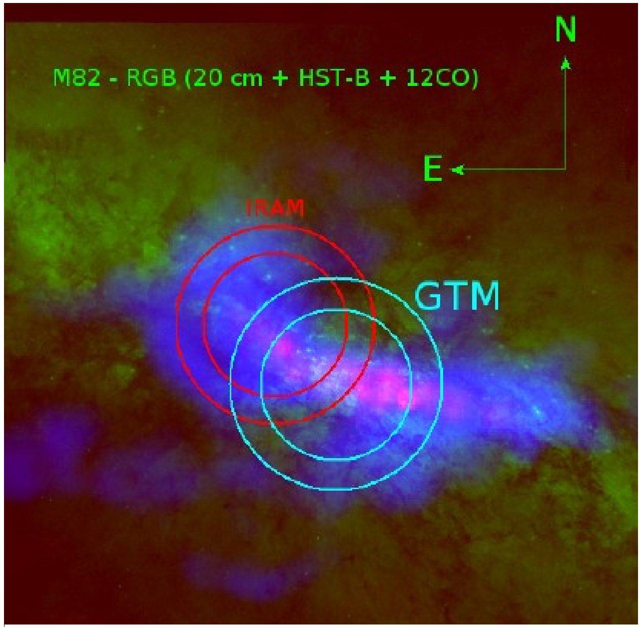
Galaxy	Type	Dist. (Mpc)	RRL	$I_L \Delta\nu_L$ ($10^{-19}\,\mathrm{W\,m^{-2}}$)	V_{Helio} ($\mathrm{km\,s^{-1}}$)	ΔV_L ($\mathrm{km\,s^{-1}}$)	References
M82	Ir	3.25	H27α	21.1±4.3			Seaquist et al. (1996)
			H30α	5.12±1.0			Seaquist et al. (1994)
			H41α	1.32±0.22			Seaquist et al. (1996)
			H53α	0.22±0.06			Puxley et al. (1989)
			H85α	$(4.6\pm0.7)\times10^{-3}$	180±10	149±25	Bell and Seaquist (1978)
			H102α	$(8.5\pm1.4)\times10^{-3}$	173±10	174±20	Bell and Seaquist (1978)
			H110α	$(1.05\pm0.1)\times10^{-2}$	163±10	293±20	Shaver et al. (1978)
			H166α	$> 1.7\times10^{-3}$	150±40	250±40	Shaver et al. (1977; 1978)
			H166α	$(5.1\pm0.8)\times10^{-3}$	254±20	338±40	Shaver et al. (1978)
NGC253	Spiral	3.4	H92α	$(4.0\pm0.4)\times10^{-3}$	217±8	189±19	Anantharamaiah and Goss (1990)
			H102α	$(1.3\pm0.3)\times10^{-2}$	132±25	309±65	Seaquist and Bell (1977)
			H110α	$(2.9\pm0.6)\times10^{-3}$	209±13	185±32	Anantharamaiah and Goss (1990)
			H166α	$(3.8\pm1.0)\times10^{-3}$	195±36	220±87	Anantharamaiah and Goss (1990)
NGC2146	Spiral	13	H53α	$(9.5\pm1.7)\times10^{-2}$	≈ 880	≈ 300	Puxley et al. (1991)
			H92α	2.7×10^{-4}	960±7	200±95	Zhao et al. (1996)
NGC1365	Seyf. II	22.0	H92α	$(12\pm2)\times10^{-4}$	1,670±80	310±110	Anantharamaiah et al. (1993)
NGC3628	S3 pec	11.5	H92α	$(8.6\pm1.5)\times10^{-4}$	864±56	170±70	Anantharamaiah et al. (1993)
IC694[a]	Sc	40.3	H92α	$(3.9\pm1.0)\times10^{-4}$	3,020±90	350±110	Anantharamaiah et al. (1993)
NGC3690[a]	Sc		H92α	$(1.5\pm0.2)\times10^{-4}$	3,080±40	210±30	Zhao et al. (1997)
Arp 220	FIR	73	H31α	>1.65±0.1			Anantharamaiah et al. (2000)
			H40α	0.39±0.05	5,513	179	Anantharamaiah et al. (2000)
			H42α	0.22±0.02	5,424	210	Anantharamaiah et al. (2000)
			H92α	3.5×10^{-4}	5,560±70	320±120	Zhao et al. (1996)
			H92α	$(8\pm1.5)10^{-4}$	5,450±20	363±45	Anantharamaiah et al. (2000)
M83	SBc/b	5	H92α	2.8×10^{-4}	500±30	95±30	Zhao et al. (1996)
NGC660	SBa pec	11.3	H92α	5.6×10^{-4}	850	377	Phookun et al. (1998)

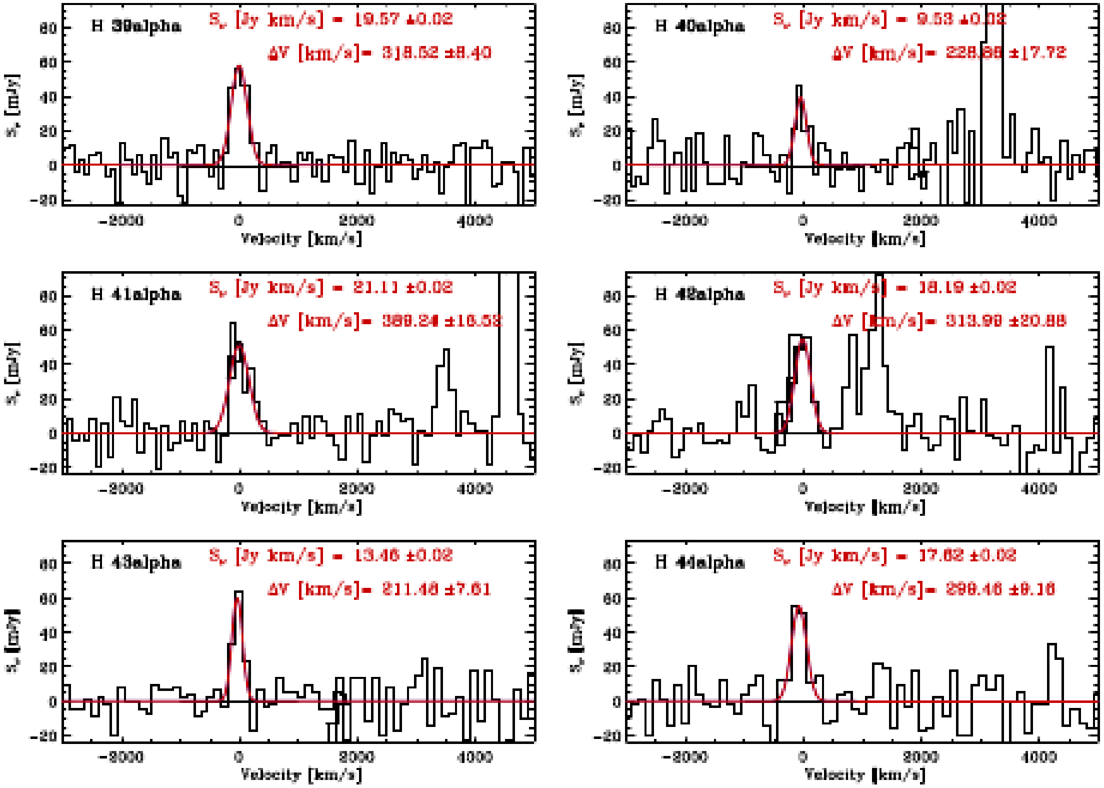
[a] IC694 and NGC3690 are an interacting system

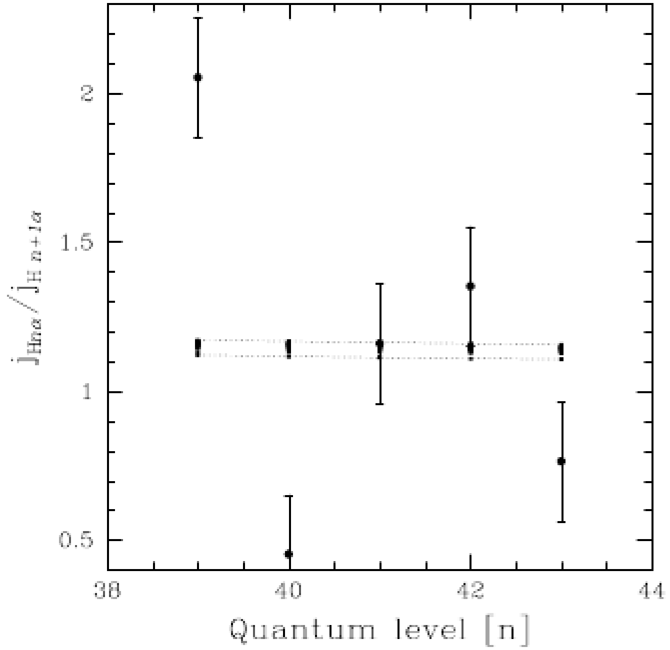
8.1 RRLs from LMT/RSR from external galaxies



8.2 RRLs from LMT/RSR from external galaxies: M82

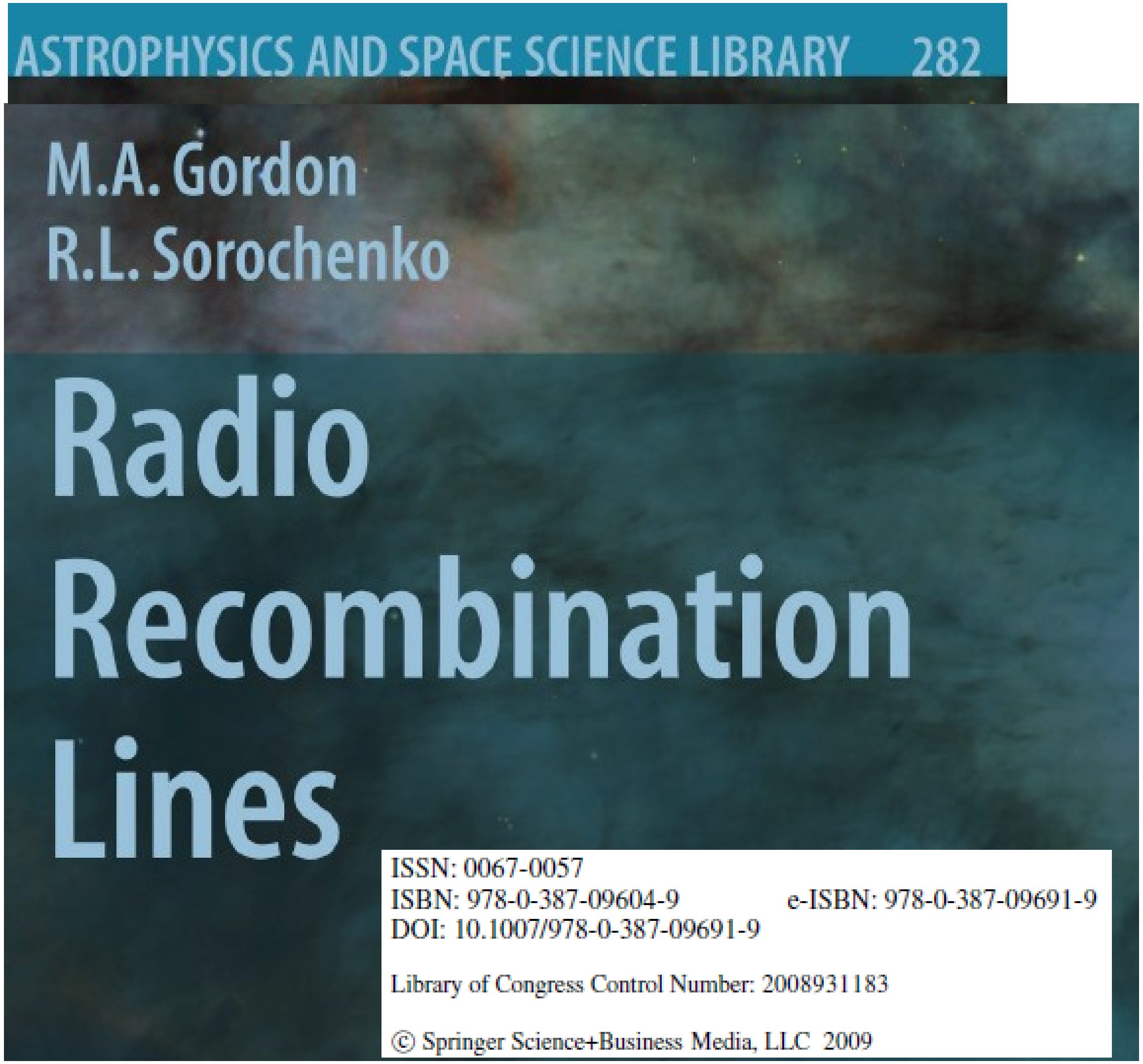






- 6 RRLs are detected in M82
- Line ratios for some lines agree with the expected values
- require higher SNR to analyze profiles

Reference:



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