Interstellar reddening correction using HeI lines

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Starburst along the life of the Universe

Interestellar extinction

- Interstellar extinction is generated by the scatter and absorption of photons by the medium between the observer and the radiation source.

- It is produced by dust grains and gas present in the interstellar medium and this mechanism is effective in photons with wavelengths comparable to the size of grains.

- The correction of the observed line fluxes for this effect is an indispensable preliminary step for the physical interpretation of the data.

Methods to determine interstellar extinction

- Using the ratio of two forbidden lines from the same upper set of levels.

- Comparing hydrogen recombination lines from two different series arising from the same upper level.

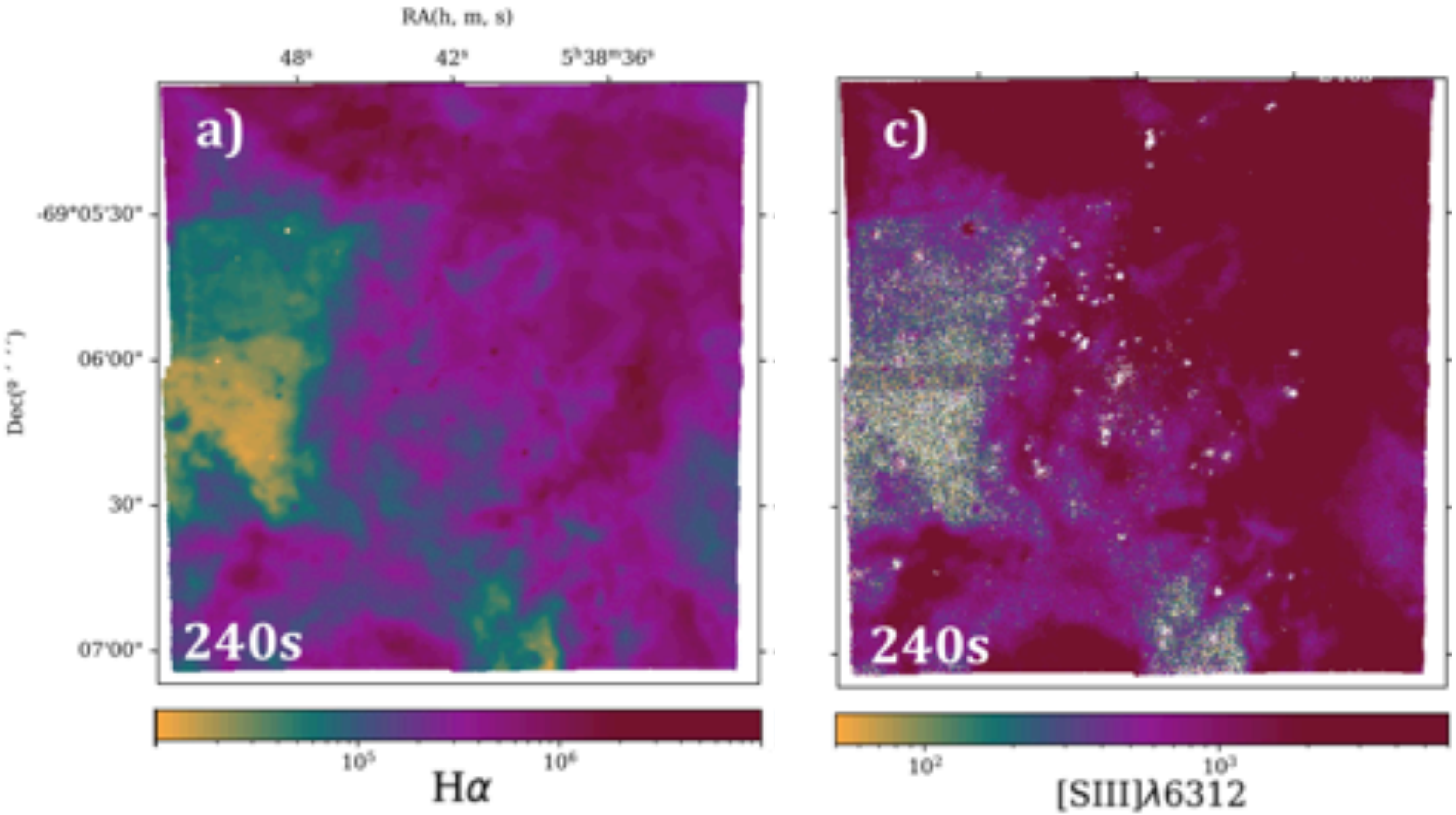
- Comparing two hydrogen recombination lines from the same series, even if they do not originate from same upper level.

The use of these strong lines can lead to selection biases when studying regions with different surface brightness

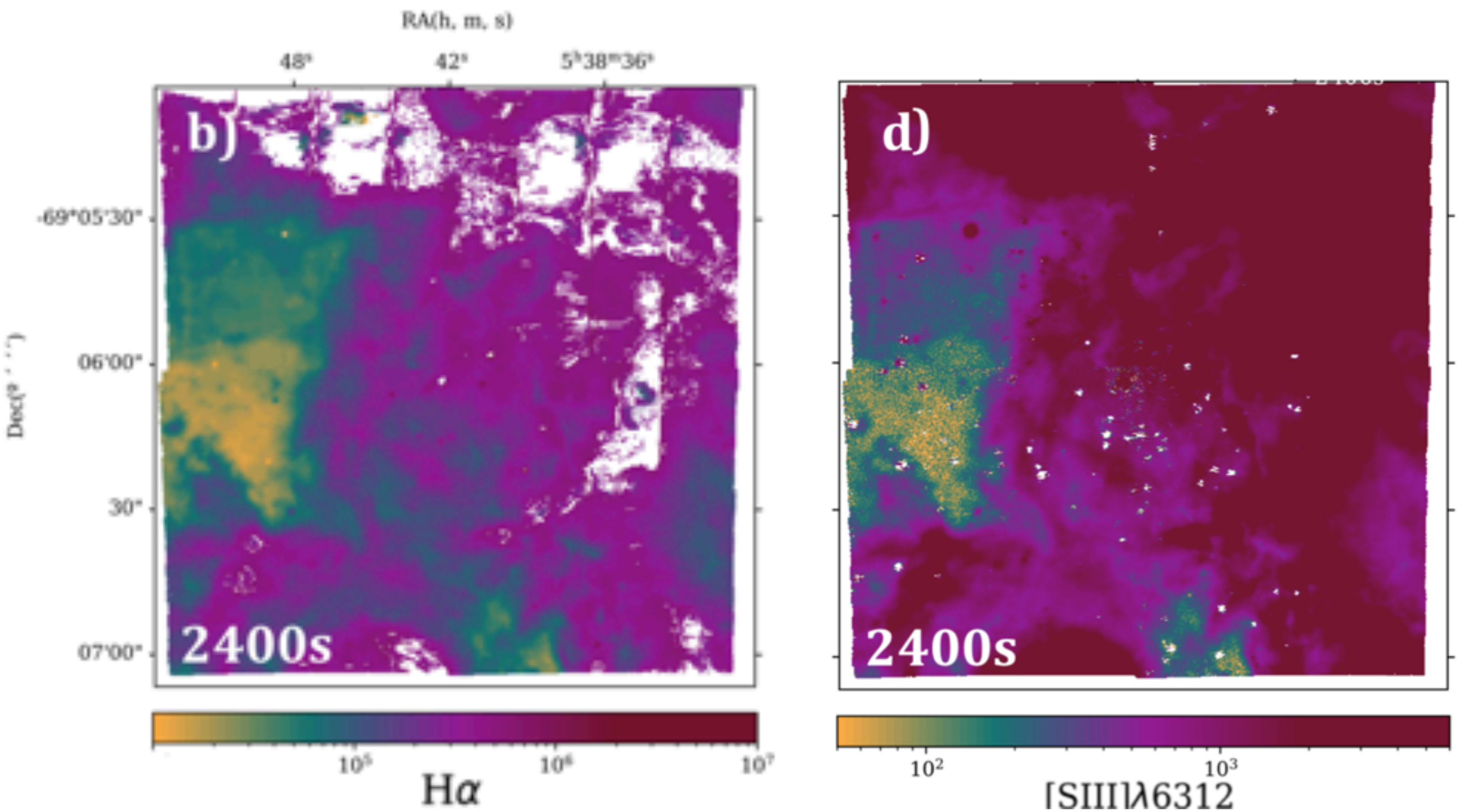
Hα/Hβ disadvantages

- Some spectrographs not including these Balmer lines.
- In extended nebulae observations are focused only in the brightest region.
- In Integral Field Spectroscopy data, we can study physical conditions of the entire nebula but cover a very large dynamical range of surface brightness.

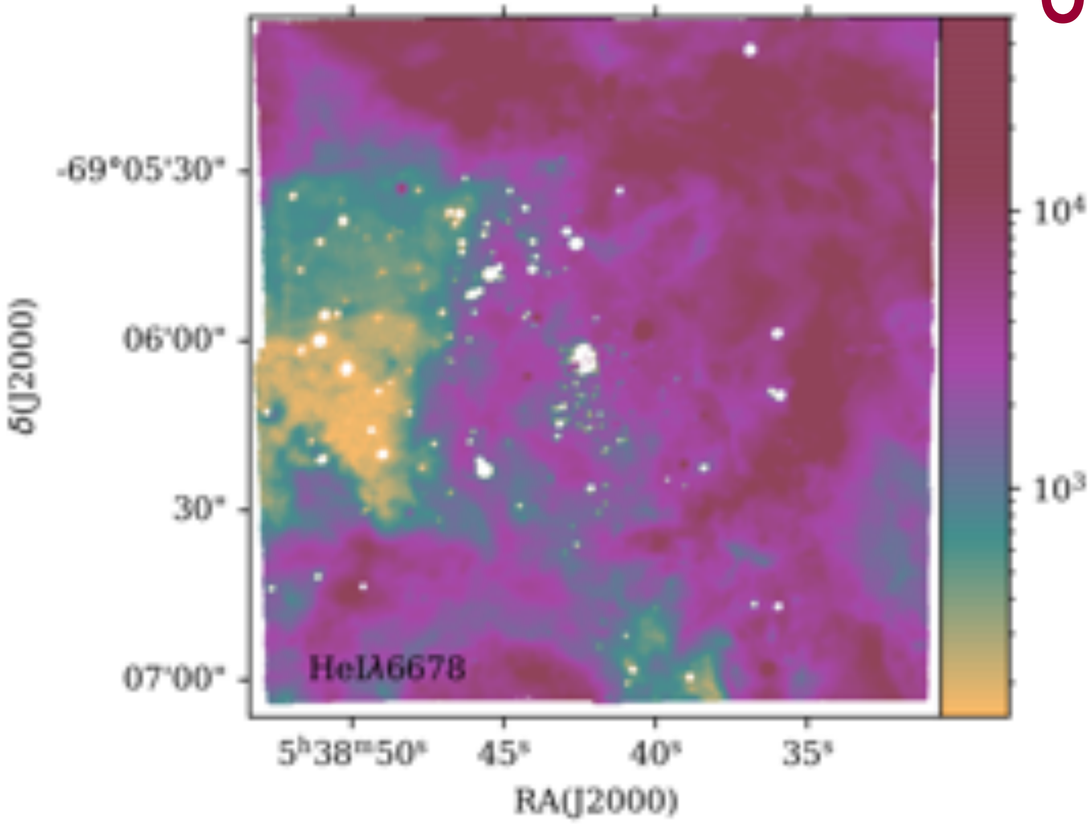
Hα/Hβ disadvantages



Hα/Hβ disadvantages

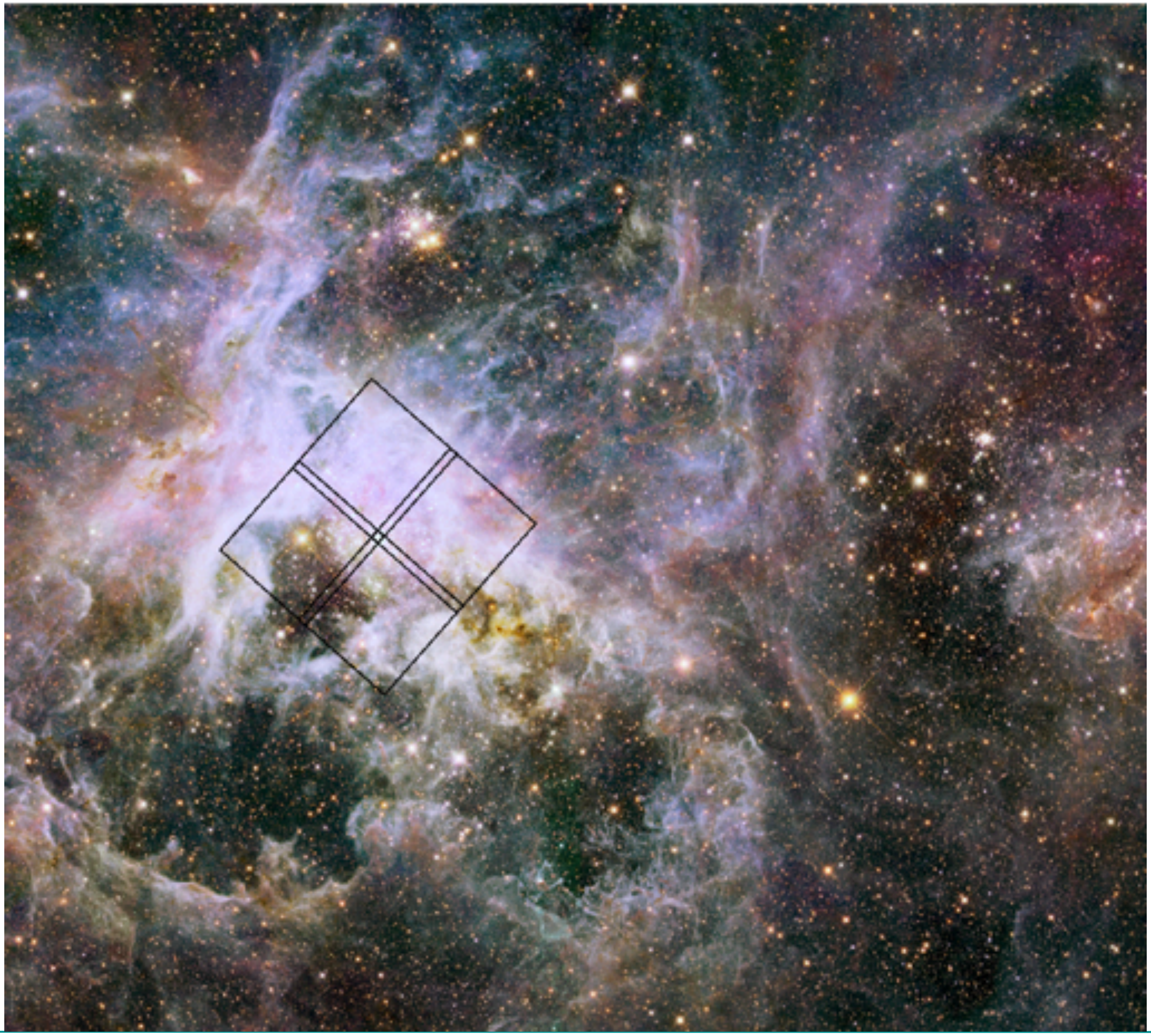


Observations



- We propose an alternative method to derive extinction corrections **based on the lines of HeI.**

Wide Field Camera 3 (WFC3) y Advanced Camera for Surveys (ACS).
Azul, banda I; verde, banda J; rojo, banda H

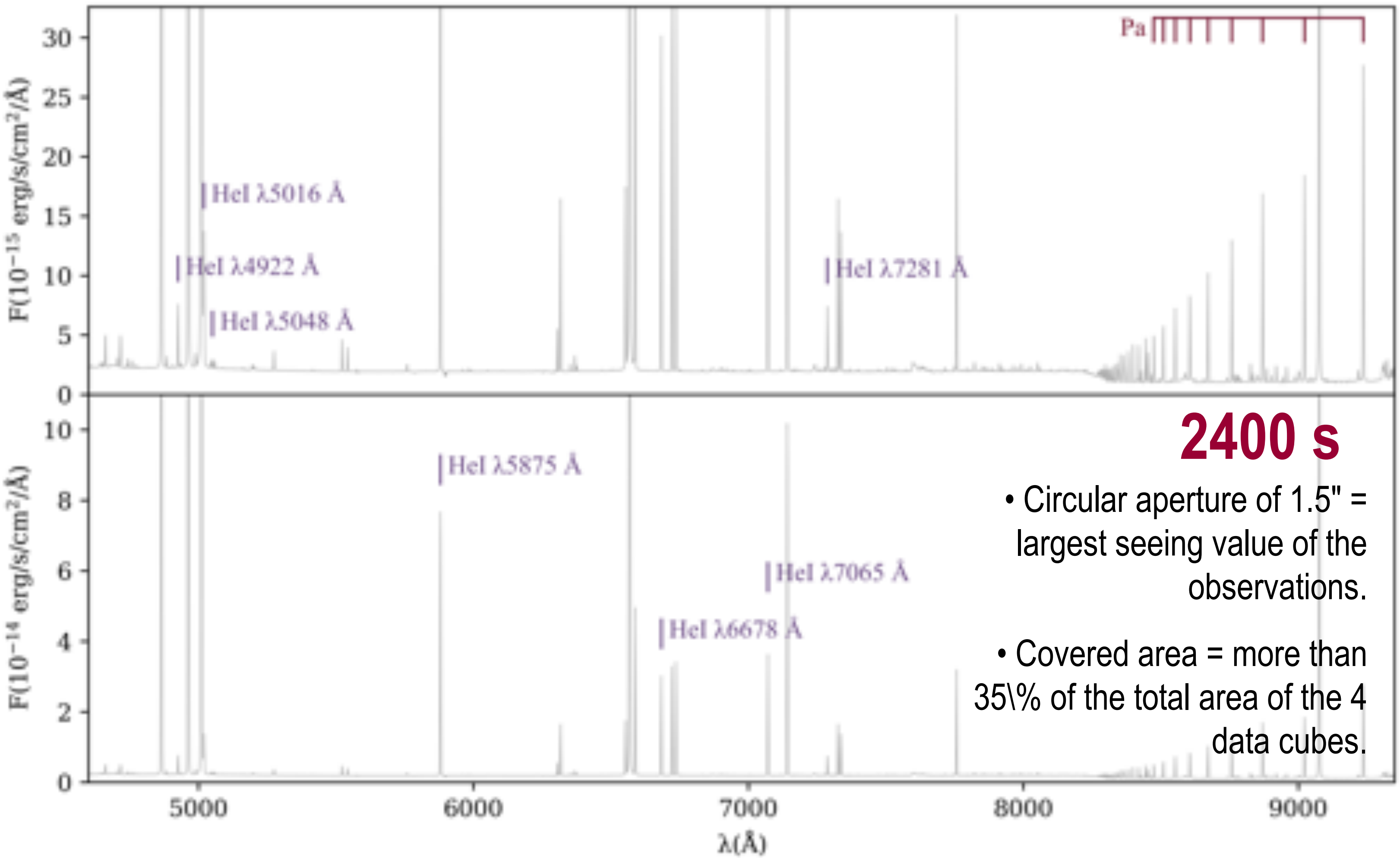


Wide Field Camera 3 (WFC3) y Advanced Camera for Surveys (ACS).
Azul, banda I; verde, banda J; rojo, banda H

1x1 minarc^2 x 4 campos

240 s y 2400 s

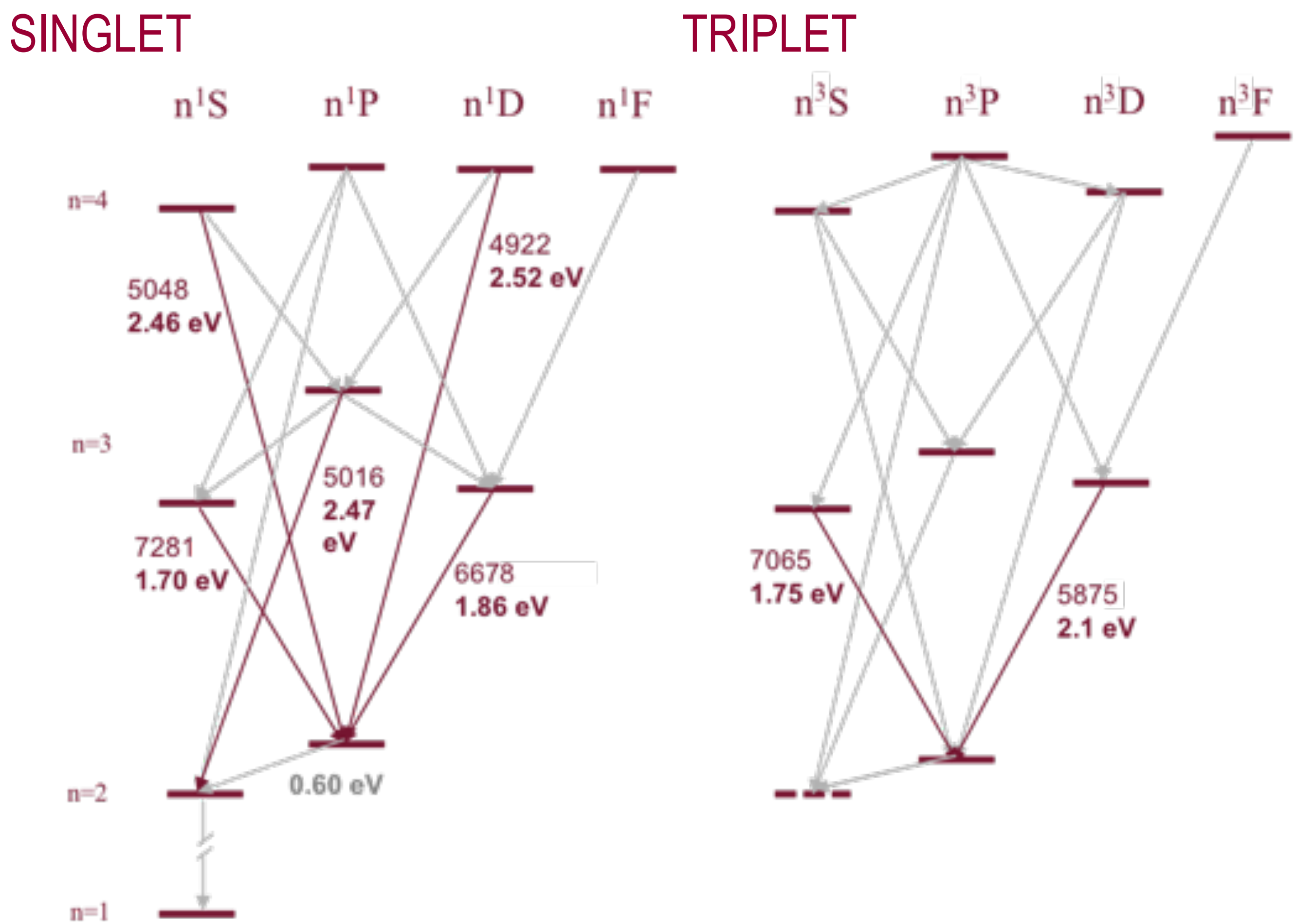
Observations



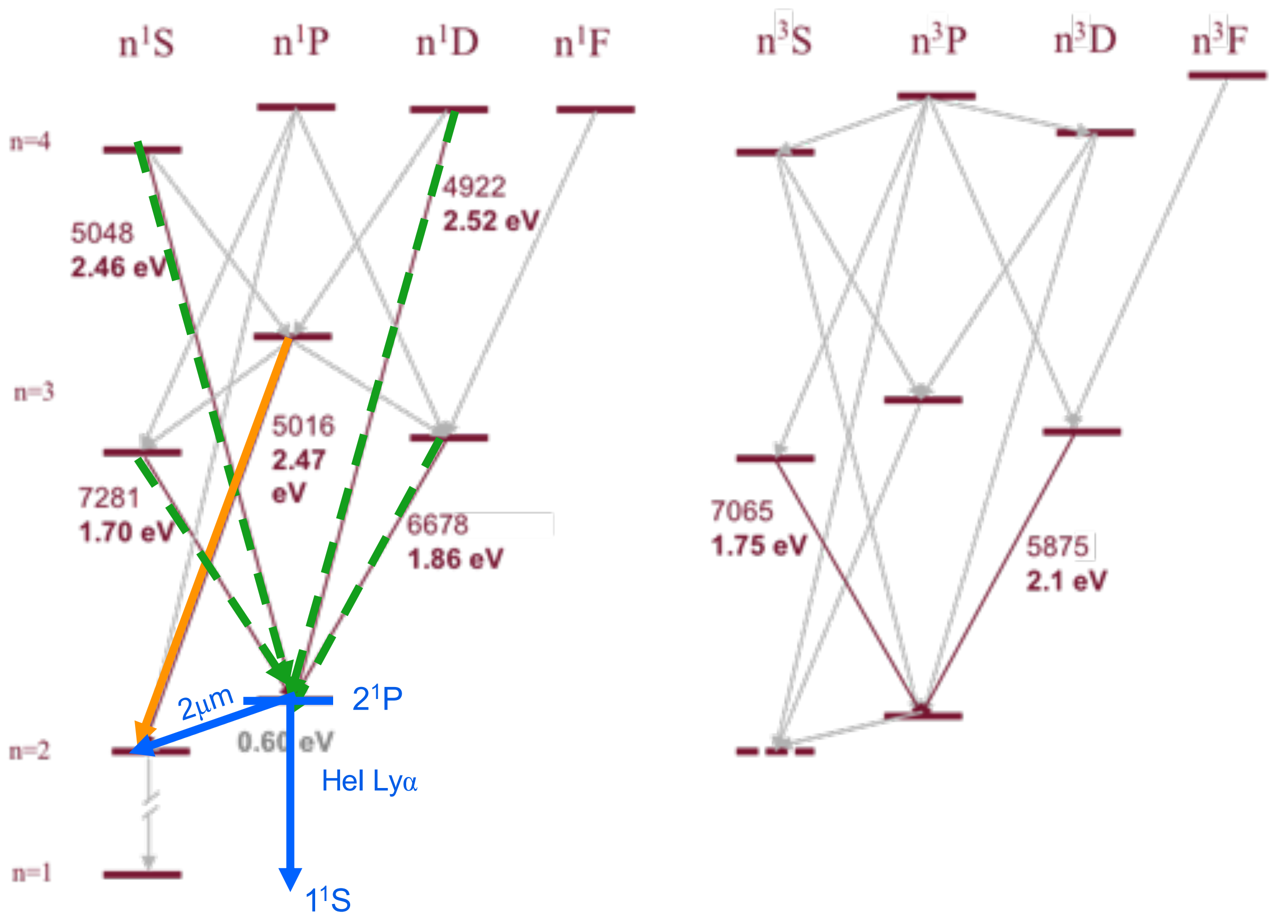
2400 s

- Circular aperture of 1.5" = largest seeing value of the observations.
- Covered area = more than 35\% of the total area of the 4 data cubes.

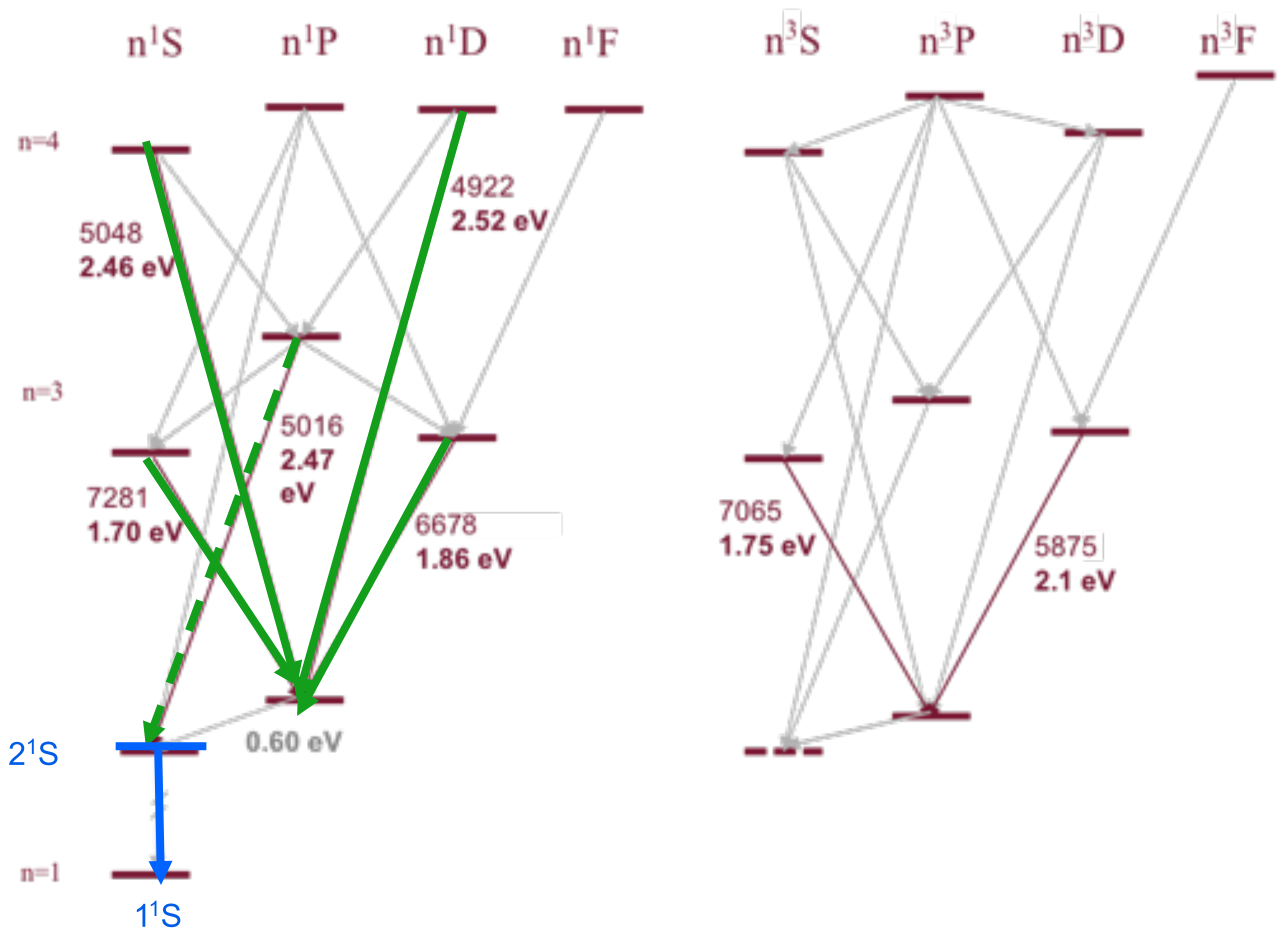
Theoretical context



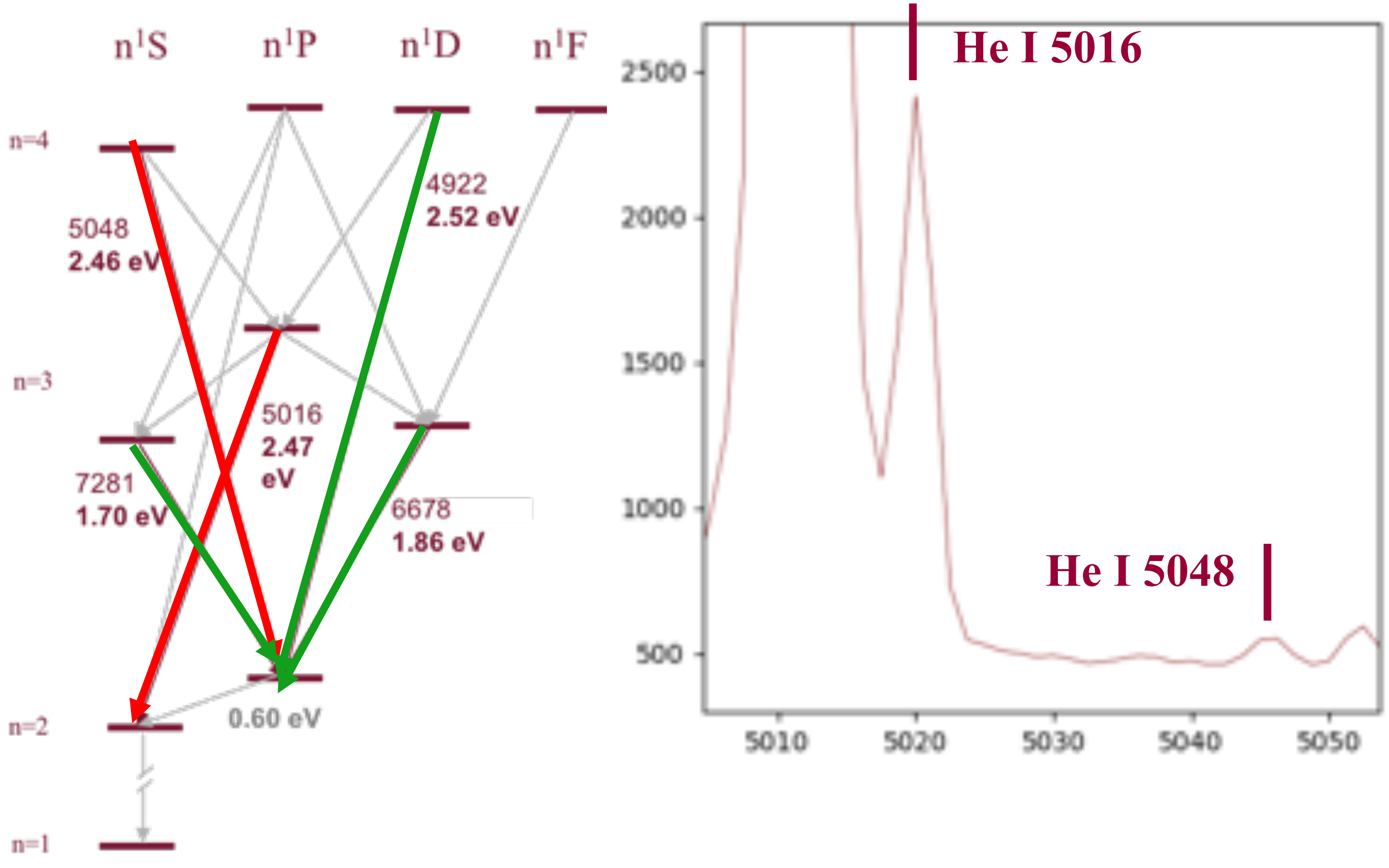
Singlet states



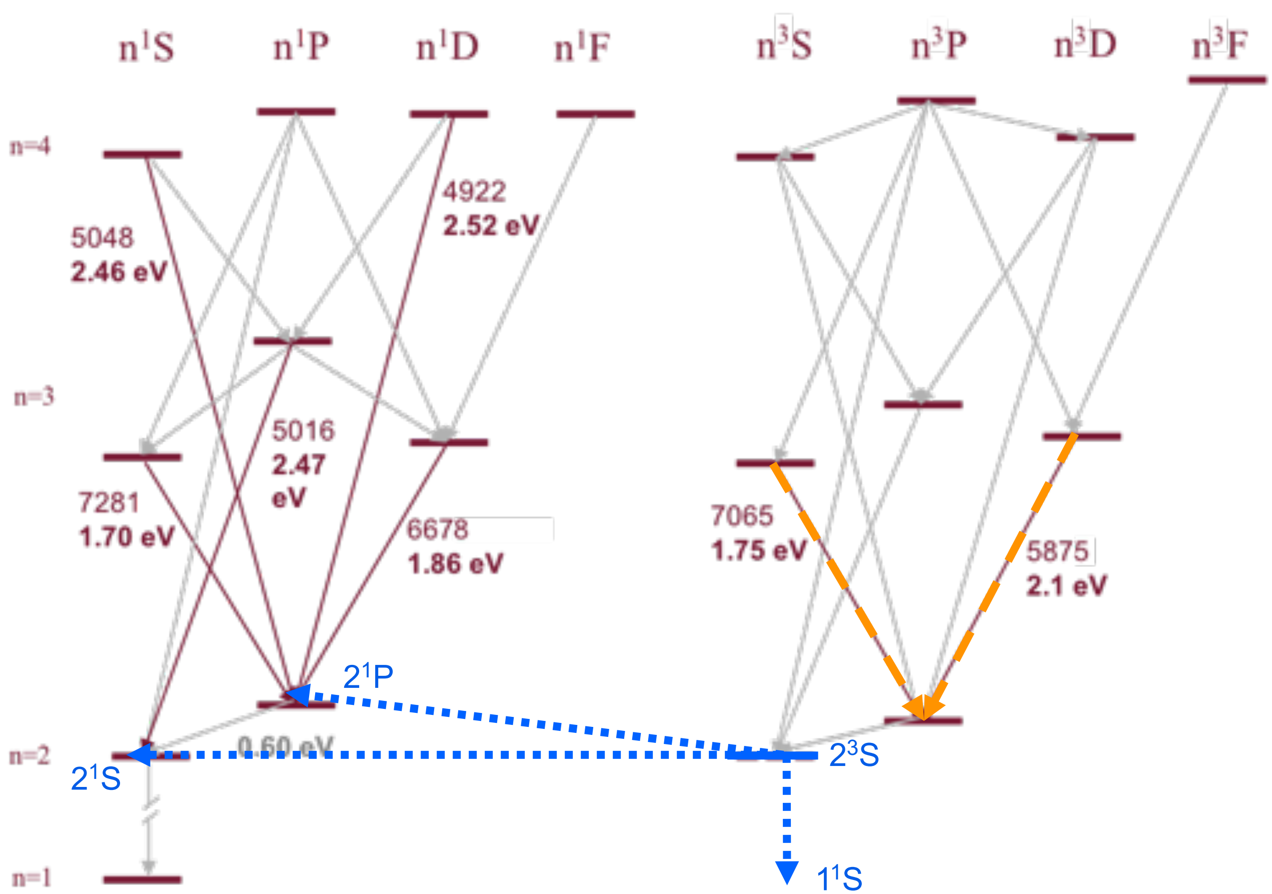
Singlet states



Singlet states



Triplet states



Collisional contribution

TABLE 8

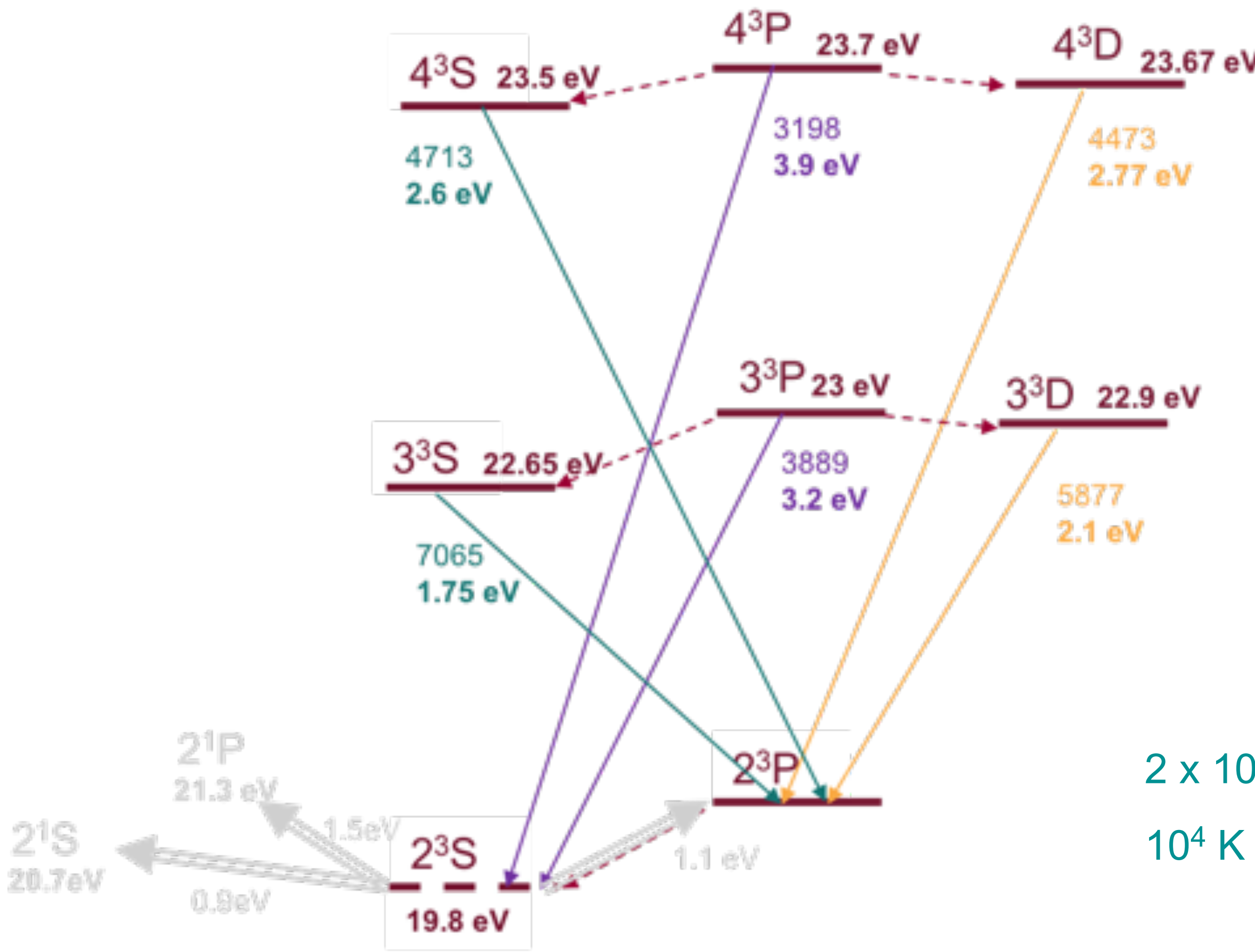
POPULATIONS OF METASTABLE $2\,^3S$ AND $2\,^1S$ AND RESULTANT COLLISIONAL CONTRIBUTIONS ($T = 20{,}000$ K)[a]

	log $n_e = 2$		log $n_e = 4$		log $n_e = 6$	
COLLISIONAL-TO-RECOMBINATION LINE CONTRIBUTION	BSS[b]	KF[c]	BSS	KF	BSS	KF
$n(2\,^3S)/n_{\mathrm{He}^+}$	1.03×10^{-7}	1.06×10^{-7}	2.04×10^{-6}	2.02×10^{-6}	2.53×10^{-6}	2.46×10^{-6}
$C/R(3890)$	0.042	0.043	0.828	0.815	1.022	0.994
$C/R(3189)$	0.023	...	0.463	...	0.571	...
$C/R(2946)$	0.004	...	0.085	...	0.105	...
$C/R(7067)$	0.152 15%	0.153	3.024	2.898	3.763	3.532
$C/R(5877)$	0.054 5%	0.055	1.077	1.043	1.343	1.271
$C/R(4715)$	0.112	...	2.223	...	2.777	...
$C/R(4473)$	0.035	0.038	0.688	0.712	0.853	0.868
$C/R(4027)$[d]	...	0.019	...	0.358	...	0.436
$C/R(18690)$	0.018	...	0.355	...	0.448	...
$n(2\,^1S)/n_{\mathrm{He}^+}$[e]	7.57×10^{-14}	...	2.32×10^{-11}	...	2.71×10^{-9}	...
$C/R(5017)$	0.015	...	0.287	...	0.359	...
$C/R(3966)$	0.009	...	0.175	...	0.218	...
$C/R(7283)$	0.054	0.052	1.063	0.991	1.338	1.208
$C/R(6680)$	0.016	0.016	0.313	0.308	0.402	0.375
$C/R(4923)$	0.013	0.014	0.262	0.267	0.331	0.325
$C/R(4389)$	...	0.011	...	0.204	...	0.248
$C/R(18701)$	0.004	...	0.082	...	0.107	...

[a] Only lines with collisional corrections, C/R, greater than 1% over the density range are shown.
[b] Current work.
[c] From Kingdon & Ferland 1995.
[d] $2\,^1S$ population not estimated in Kingdon & Ferland 1995.
[e] Collisions to $n = 5$ not included in current work. See § 3.1.

Robert A. Benjamin et al. 1999

Radiative transfer



2×10^4 K = 1.6 eV

10^4 K = 0.8 eV

Radiative transfer

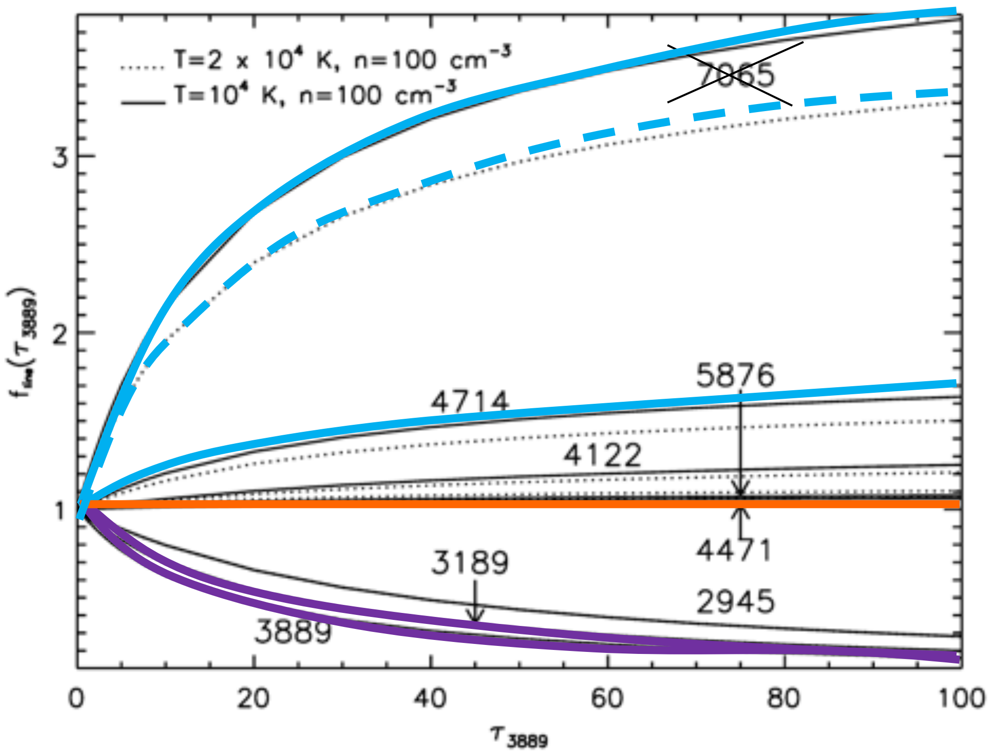


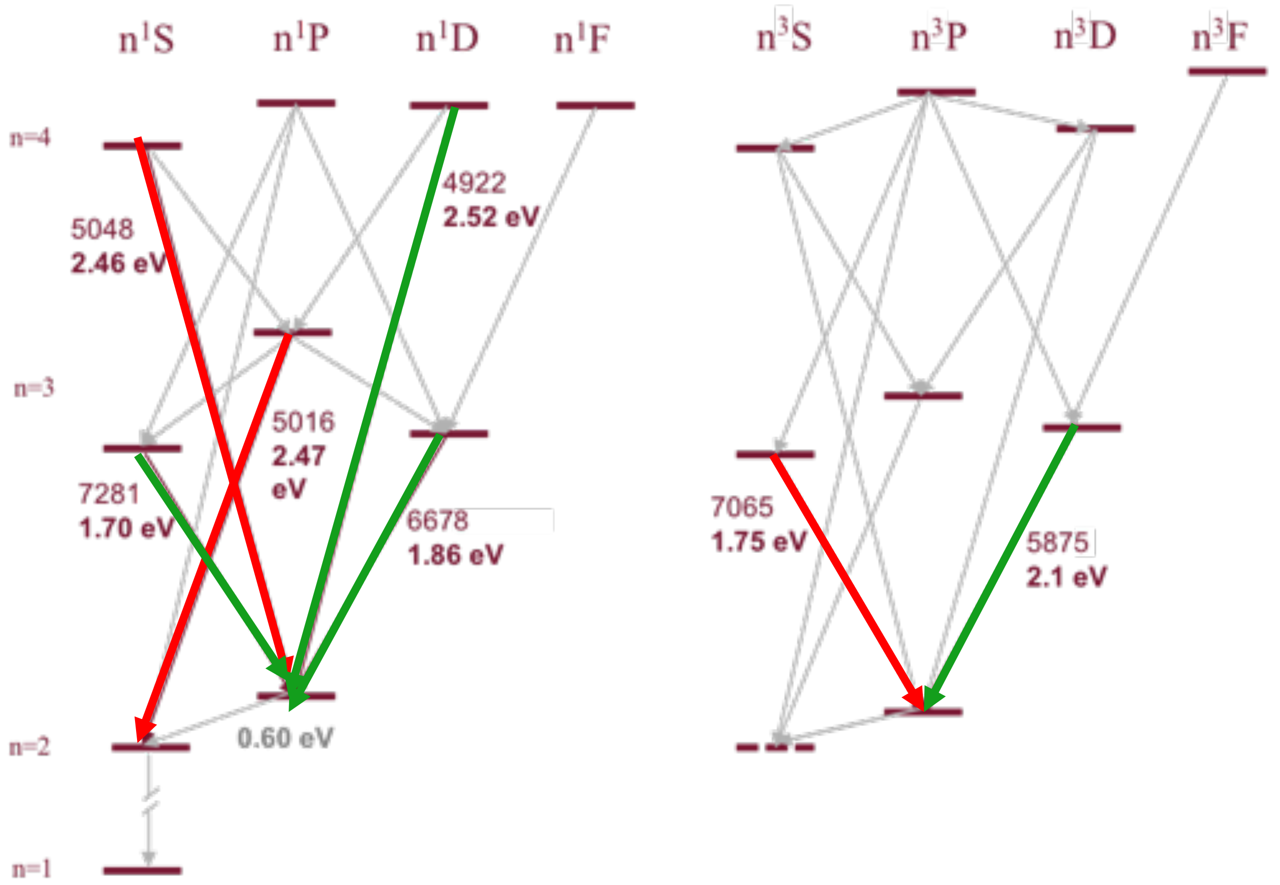
FIG. 2.—Optical depth correction factor for selected optical lines for cases with a particle density of $n_H = 100$ cm^{-3} and two different temperatures.

Robert A. Benjamin et al. 2002

2×10^4 K = 1.6 eV

10^4 K = 0.8 eV

Theoretical context



Case B of recombination

Line	$f(\lambda)^a$	I_λ/I_{ref} ^{b}
Hβ	0	1.000
HeI λ4922 Å	-0.014	0.345
HeI λ5875 Å	-0.209	3.518
Hα	-0.313	2.863
HeI λ6678 Å	-0.329	1.000
HeI λ7065 Å	-0.377	0.621
HeI λ7281 Å	-0.402	0.187
Pa17	-0.514	0.004
Pa16	-0.518	0.004
Pa15	-0.521	0.005
Pa14	-0.525	0.007
Pa13	-0.531	0.008
Pa12	-0.537	0.011
Pa11	-0.546	0.014
Pa10	-0.557	0.018
Pa9	-0.572	0.025

[a] Miller & Mathews (1972), $R_v = 3.2$.
[b] Luridiana et al. (2015), $n_e(cm^{-3}) = 10^2$, $T(K) = 10^4$.

Table 1. Empirical values of the normalised logarithmic extinction at the wavelengths of the different HeI emission lines from Miller & Mathews (1972), and the ratio of these lines to the λ 6678 Å reference line as calculated by the PyNeb (Luridiana et al. 2015) tool for $T = 10^4$ K and $n_e = 10^2$ cm^{-3}, using Storey & Hummer (1995) and Porter et al. (2012) atomic data for hydrogen and helium respectively.

The fluxes of two lines separated in wavelength are measured.

The most intense line of those left to us will be selected as a reference: **HeI 6678**

A typical ratio of these fluxes is assumed.

Pyneb, Luridiana et al. (2015)

Datos atómicos de

Storey & Hummer (1995) para H

Porter et al. (2012) para He

An extinction curve is assumed.

Miller & Mathews (1972), R_v = 3.2

1-Interstellar extinction correction using the ratio of two recombination lines

Line	f(λ)[a]	I_λ/I_{ref} [b]
Hβ	0	1.000
HeI λ4922 Å	-0.014	0.345
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$$c(H\beta) = -\frac{1}{f(\lambda) - f(H\beta)} \cdot \left[log\left(\frac{F_\lambda}{F_{H\beta}}\right) - log\left(\frac{I_\lambda}{I_{H\beta}}\right)\right]$$

$$c(H\beta) = -\frac{1}{f(\lambda) - f(HeI\lambda6678)} \cdot \left[log\left(\frac{F_\lambda}{F_{HeI\lambda6678}}\right) - log\left(\frac{I_\lambda}{I_{HeI\lambda6678}}\right)\right]$$

1-Interstellar extinction correction using the ratio of two recombination lines

- Hydrogen reddening from short exposure spectra (240 s).
  - Mean relative errors in fluxes of Hβ line -> 0.92%
  - Mean relative errors in fluxes of Hα line -> 0.15%
  - Absolute mean error of c(Hβ) -> 0.02.

- Helium reddening from long exposure spectra (2400 s).
  - Mean relative errors in fluxes of HeI λ 5875 line -> 0.37%
  - Mean relative errors in fluxes of HeI λ 6678 line -> 1.37%
  - Absolute mean error of c(Hβ) -> 0.05.

2-Interstellar extinction correction using a linear regression

Line	$f(\lambda)^a$	I_λ/I_{ref} [b]
$H\beta$	0	1.000
HeI λ4922 Å	-0.014	0.345
HeI λ5875 Å	-0.209	3.518
$H\alpha$	-0.313	2.863
HeI λ6678 Å	-0.329	1.000
HeI λ7065 Å	-0.377	0.621
HeI λ7281 Å	-0.402	0.187
Pa17	-0.514	0.004
Pa16	-0.518	0.004
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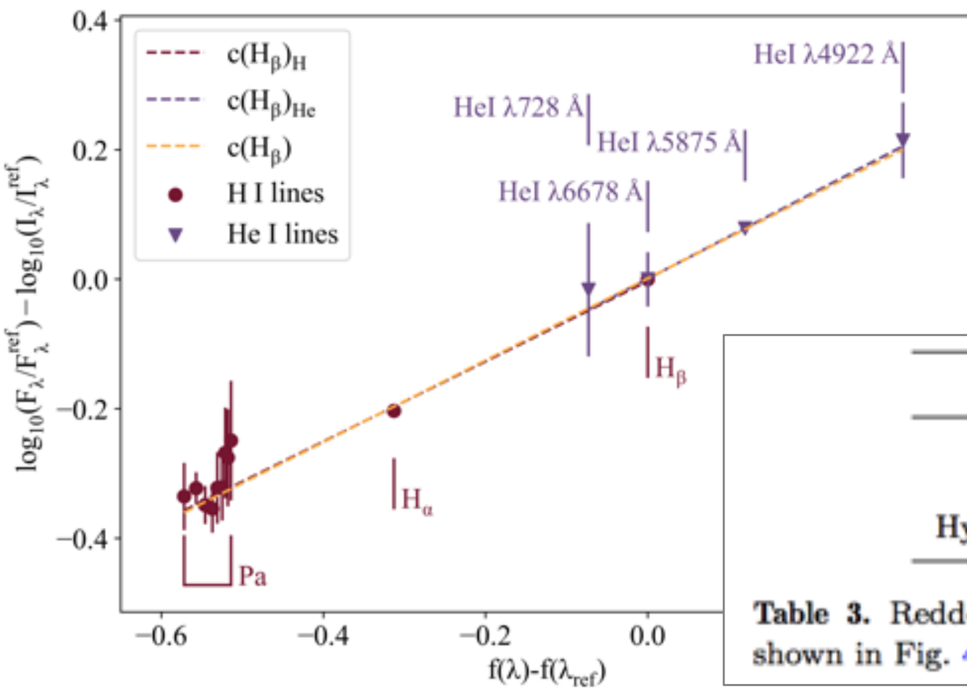
$$log_{10}\left(\frac{F_\lambda}{F_{H\beta}}\right) - log_{10}\left(\frac{I_\lambda}{I_{H\beta}}\right) = -c(H\beta)(f(\lambda) - f(H\beta))$$

$$log_{10}\left(\frac{F_\lambda}{F_{HeI\lambda6678}}\right) - log_{10}\left(\frac{I_\lambda}{I_{HeI\lambda6678}}\right) = \\ = -c(H\beta)(f(\lambda) - f(HeI\lambda6678))$$

2-Interstellar extinction correction using a linear regression

The fits obtained for hydrogen lines, helium lines and all the lines together are consisting with each other and the intercept is compatible with zero.



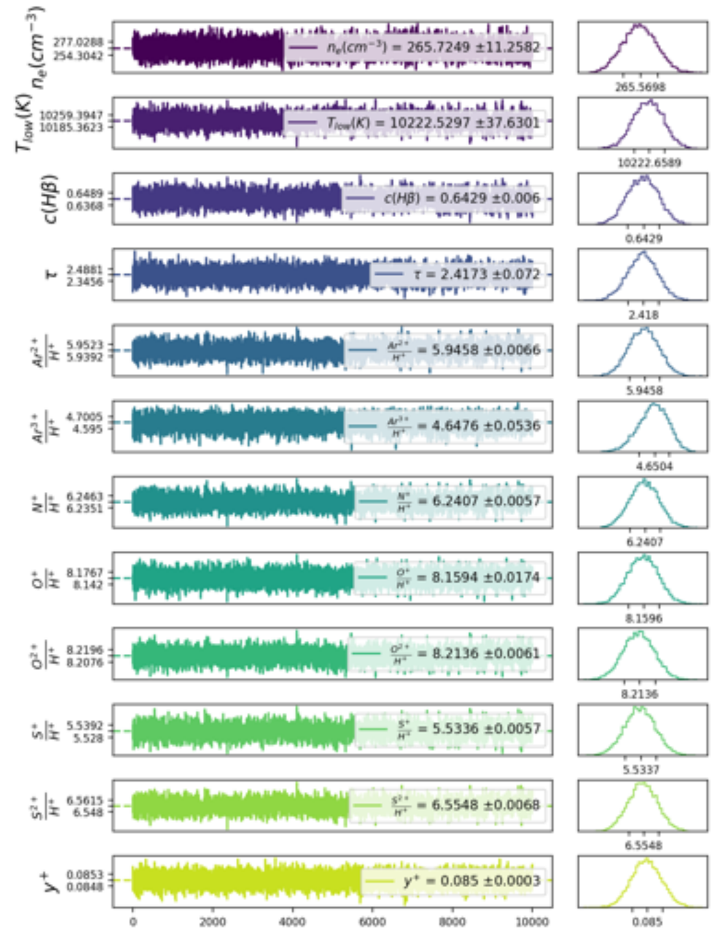
Fit	$c(H\beta)$
Hydrogen	0.619 ± 0.018
Helium	0.650 ± 0.050
Hydrogen and Helium	0.632 ± 0.010

Table 3. Reddening constant values obtained from the fitting shown in Fig. 4 for a randomly selected emission region.

Other codes

- We have introduced the derived methodology in the Bayesian algorithm described in Fernández et al. (2019).
- It simultaneously fits a 14 parameters chemical model, obtaining results which are fully compatible with those reported here

Parameter	True value	Mean	Standard deviation
$n_e(cm^{-3})$	None	265.7249	11.2582
$T_{low}(K)$	None	10222.5297	37.6301
$\frac{Ar^{2+}}{H^+}$	None	5.9458	0.0066
$\frac{Ar^{3+}}{H^+}$	None	4.6476	0.0536
$\frac{N^+}{H^+}$	None	6.2407	0.0057
$\frac{O^+}{H^+}$	None	8.1594	0.0174
$\frac{O^{2+}}{H^+}$	None	8.2136	0.0061
$\frac{S^+}{H^+}$	None	5.5336	0.0057
$\frac{S^{2+}}{H^+}$	None	6.5548	0.0068
$c(H\beta)$	None	0.6429	0.006
y^+	None	0.085	2.714e − 04
τ	None	2.4173	0.072



Underlying stellar absorption

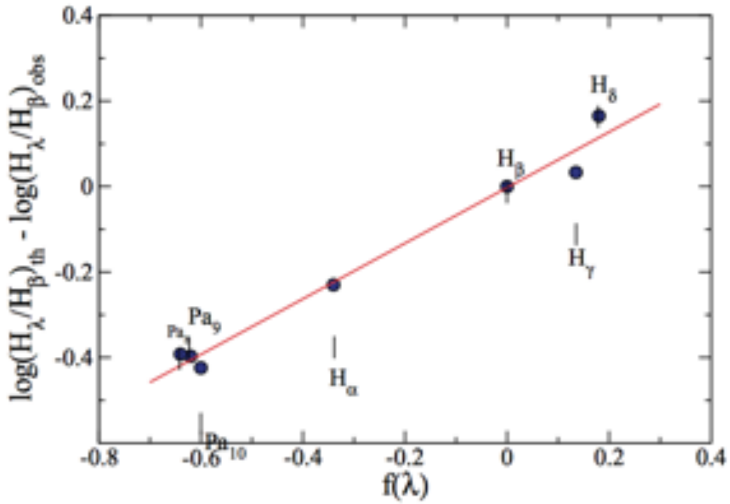
The underlying stellar absorption is less important than in the case of Helium.

Helium lines:

- EW(He I 4471) = 0.4 Å
  (Izotov et al. 2007;
  González Delgado et al. 2005)
- EW(He I 3889)/ EW(He I 4471) = 1 Å
- EW(He I 5876)/ EW(He I 4471) = 0.8 Å
  (Leitherer et al. 1999; Izotov et al. 2010;
  González Delgado et al. 2005)
- EW(He I 6678)/ EW(He I 4471) = 0.4 Å
  (Leitherer et al. 1999; Izotov et al. 2010)
- EW(He I 7065)/ EW(He I 4471) = 0.4 Å

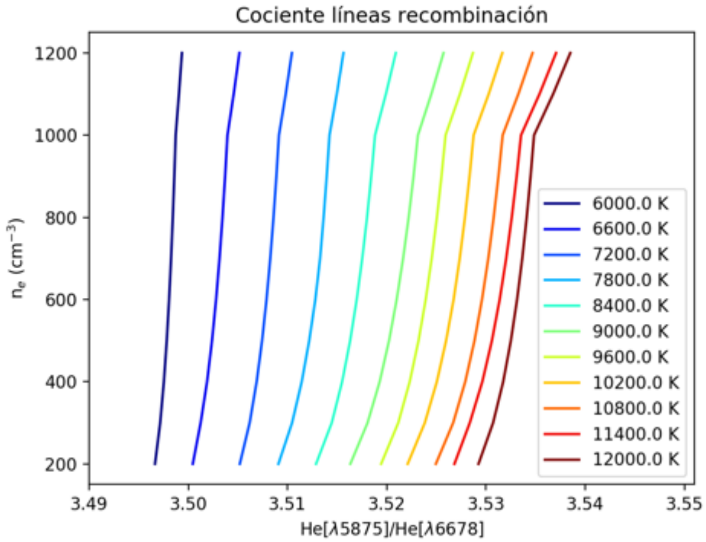
Hydrogen lines:

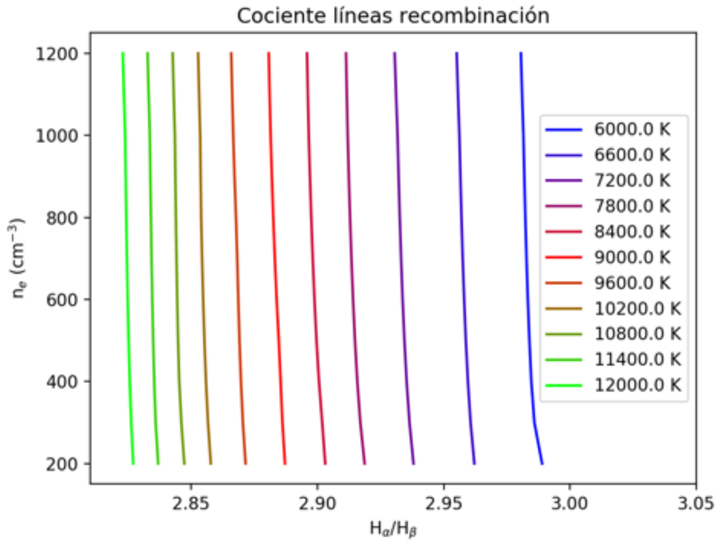
- EW(H) = 2 Å
  (McCall, Rybski & Shields 1985;
  Skillman & Kenicutt 1993)



Izotov et al. 1994.

Temperatures and densities





- Bootstrap model
  Temperatures, 8000 K and 14000 K
  Densities, 50-500 cm^{-3}
  106 repeats, resampling with replacement
  PyNeb

$\sigma(H) = 0.0185$
$\sigma(He) = 0.0041$

The ratio of HeI lines are less affected by temperatura and density variations.

Conclusions

1- **Both methods** of extinction derivation, using HI or HeI recombination lines, **are fully compatible** within the errors with each other and the errors in the determination of reddening constant get considerably reduced when both methods are used simultaneously.

2- **The results** presented in this work **will allow to study spatially resolved nebulae in their full extension**, analysing both high and low surface brightness regions simultaneously in a single moderate-to-long exposure pointing.

3- **We can recover saturated images from the archive** of different telescopes .

4- **We can determine interestellar extinction with** existing and coming up **spectrographs that not includes Balmer lines.**

Thank you!

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Starburst along the life of the Universe
May 19, 2022