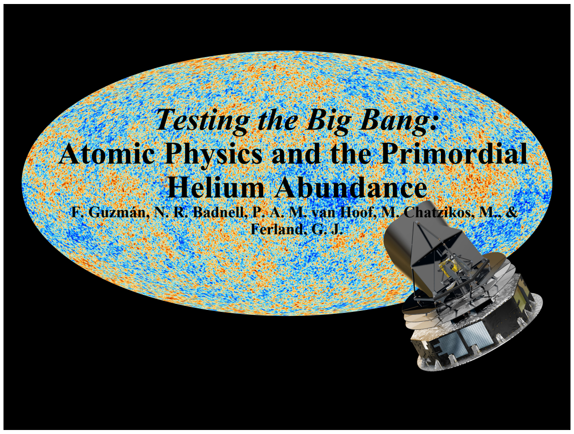
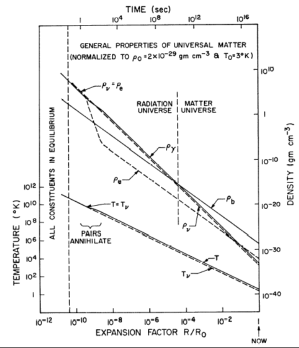
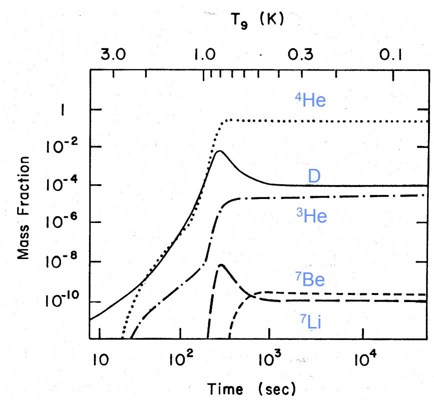


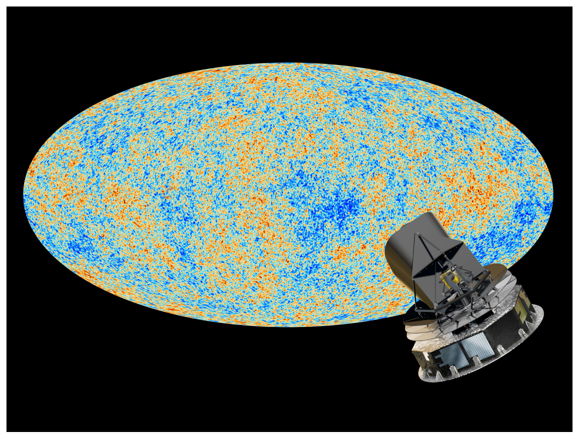
ON THE SYNTHESIS OF ELEMENTS AT VERY HIGH TEMPERATURES*

ROBERT V. WAGONER, WILLIAM A. FOWLER, AND F. HOYLE
California Institute of Technology, Pasadena, California, and Cambridge University

Received September 1, 1966







Λ CDM Cosmology & Planck

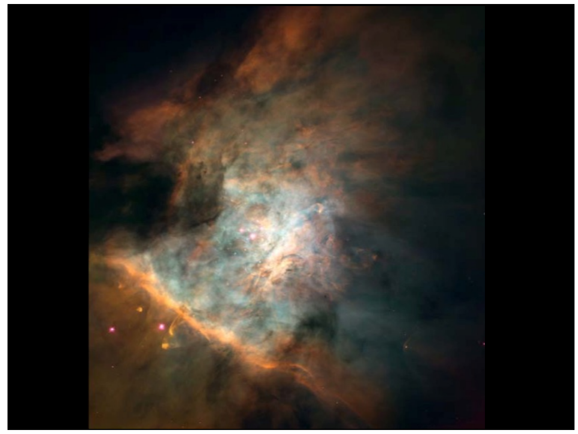
- **six parameters,**
  – the age of the universe
  – the density of atoms
  – the density of matter
  – the amplitude of the initial fluctuations
  – the scale dependence of this amplitude, and
  – the epoch of first star formation
- **fit all cosmological data**
  – Spergel, Science, 2015

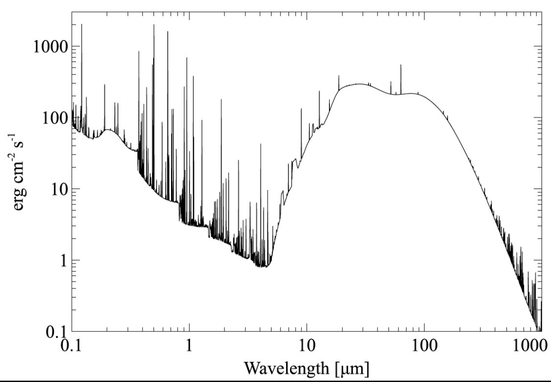
Planck 2014 Results XIV (~4400 cites)

A&A 571, A16 (2014)

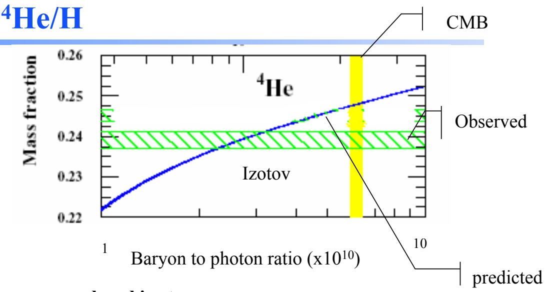
Table 2. Cosmological parameter values for the six-parameter base ΛCDM model.

Parameter	*Planck* Best fit	*Planck* 68% limits	*Planck*+lensing Best fit	*Planck*+lensing 68% limits	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048





^{4}He/H



- **produced in stars**
  - But O/H proportional to extent of contamination
- **but great precision is required**

The most recent paper

Mon. Not. R. Astron. Soc. **000**, 1–18 (2012) Printed 1 September 2014 (MN LaTeX style file v2.2)

A new determination of the primordial He abundance using the He I λ10830Å emission line: cosmological implications

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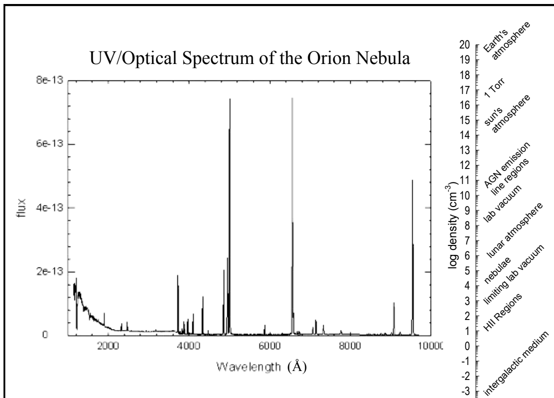
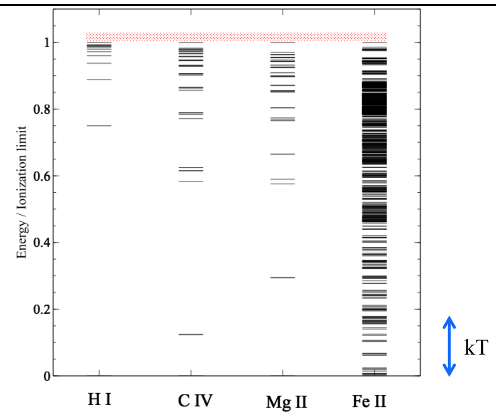
[2] *Astronomy Department, University of Virginia, P.O. Box 400325, Charlottesville, VA 22904, USA*

5 COSMOLOGICAL IMPLICATIONS

The primordial He mass fraction we have derived is higher (at the 3.4 σ level) than the SBBN value of 0.2477 ± 0.0001 inferred from analysis of the temperature fluctuations of the cosmic microwave background (CMB) radiation observed by the *Planck* satellite (Ade et al. 2013), in the context of the standard spatially flat six-parameter ΛCDM model. This may indicate small deviations from the standard rate of Hubble expansion in the early Universe. These deviations

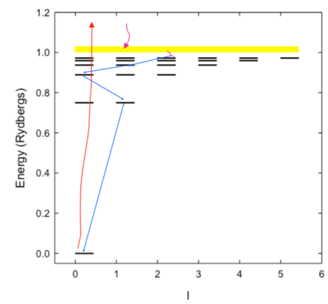


Osterbrock & Ferland (AGN3)

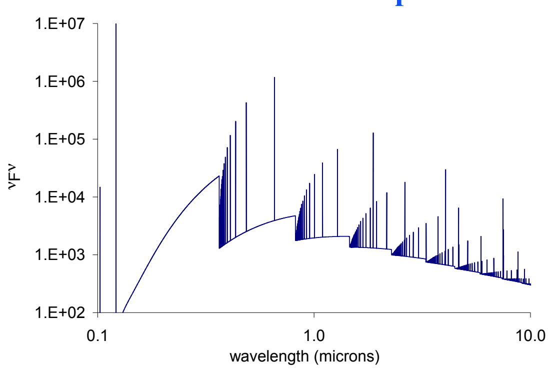


Life history of an Orion electron

- H^0 ground state
  - 1 day
- Suprathermal
  - 1 second
- Thermal
  - 1 yr
- H^0 excited states
  - 10^{-7} s
- H^0 ground state

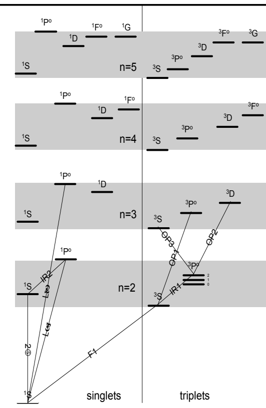


Pure H^+ recombination spectrum

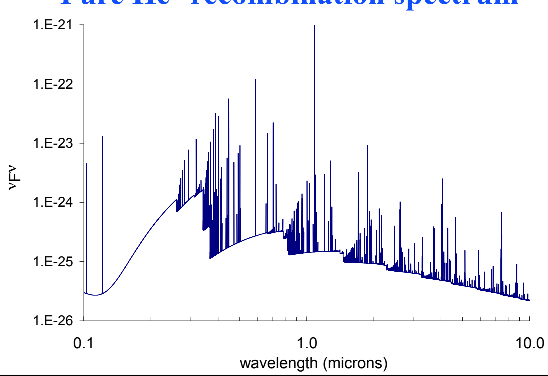


Helium

energy
(not to scale)



Pure He^+ recombination spectrum



He/H from H II regions

For a pair of lines the emission ratio is

$$\frac{I(\mathrm{He\,I})}{I(\mathrm{H\,I})} = \frac{n(\mathrm{He}^+)n_e}{n(\mathrm{H}^+)n_e} \frac{\alpha_{eff}(\mathrm{He\,I})}{\alpha_{eff}(\mathrm{H\,I})} \frac{\nu_{\mathrm{HeI}}}{\nu_{\mathrm{HI}}}$$

then

$$\frac{n(\mathrm{He}^+)}{n(\mathrm{H}^+)} = \frac{\alpha_{eff}(\mathrm{H\,I})}{\alpha_{eff}(\mathrm{He\,I})} \frac{\nu_H}{\nu_{He}} \frac{I(\mathrm{He\,I})}{I(\mathrm{H\,I})}$$

$$\approx \frac{n(\mathrm{He})}{n(\mathrm{H})}$$

Can we predict the recombination coefficients to 1% accuracy?

Predicting α_{eff}

- Radiative recombination rates are derived from photoionization cross sections
- Downward cascades, photon emission, depend on transition probabilities
- Collisional transitions occur too
  - These are the problem

Predicting α_{eff}

- Menzel & Baker 1930's
- Seaton 1950's
- Seaton students 1960s – 1990s
  - Pengelly, Brocklehurst, Storey
- Burgess & Summers 1970s
- Ryan Porter's PhD work, in Cloudy
  - Porter+, 2005, 2007, 2009, 2012
  - Bauman+05

Mon. Not. R. Astron. Soc. 393, L36–L40 (2009) doi:10.1111/j.1745-3933.2008.00593.x

Uncertainties in theoretical He I emissivities: H II regions, primordial abundance and cosmological recombination

R. L. Porter,[1,2★] G. J. Ferland,[1,2] K. B. MacAdam[1] and P. J. Storey[3]
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[3]Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT

Table 1. Assumed uncertainties in helium atomic data.

Conditions	Optimistic (per cent)	Pessimistic (per cent)
Rad. recomb. coefficients (direct)		
$n >= 5$ and $L > 3$	0	0.1
$n >= 5$ and $L <= 3$	0.01-0.7	≤4
$n < 5$	0.01-0.7	≤4
E1 transition probabilities		
$n_u, n_l < 10$ and $L < 7$	0.01	0.2
$n_u, n_l < 10$ and $L >= 7$	0	0.01
$n_u > 10$, $n_l < 5$ and $L_l <= 2$	0.02	0.2
$n_u > 10$, $L_u \geq 2$ and $L_l \geq 2$	0.6	4
$n_u > 10$, $n_l < 10$ other	1	7
$n_u, n_l > 10$	10	10

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$n_u, n_l < 10$ and $L >= 7$	0	0.01
$n_u > 10$, $n_l < 5$ and $L_l <= 2$	0.02	0.2
$n_u > 10$, $L_u \geq 2$ and $L_l \geq 2$	0.6	4
$n_u > 10$, $n_l < 10$ other	1	7
$n_u, n_l > 10$	10	10
Other transition probabilities		
$2p\,^3P_1 - 1s\,^1S$	1	5
$2p\,^3P_2 - 1s\,^1S$	1	1
$2s\,^3S - 1s\,^1S$ (2ν)	10	30
$2s\,^3S - 1s\,^1S$ (M1)	1	20
$2s\,^1S - 1s\,^1S$	1	5
All others	1	1
Collisional de-excitation		
$n_u <= 5$ and $n_l <= 2$	10	30
$\Delta n = 0$	20	30
Otherwise	20	30

Monthly Notices of the Royal Astronomical Society LETTERS
Mon. Not. R. Astron. Soc. (2012) doi:10.1111/j.1745-3933.2012.01300

Improved He I emissivities in the case B approximation

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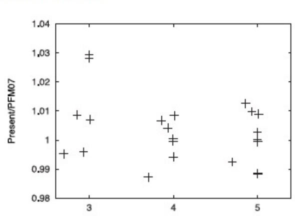
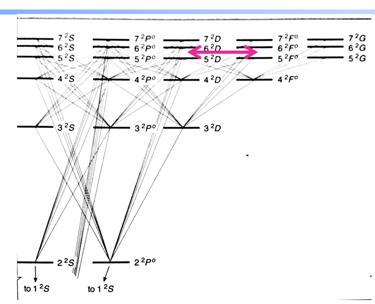
- Hummer & Storey (1998) R-matrix photoionization cross sections removed radiative recombination rate coefficients as a source of uncertainty.



Energy-degenerate l-changing collisions



- Pengelly & Seaton (1964) is the classic reference

The Vrinceanu+ update

- Vrinceanu & Flannery 2002 PRA
- Vrinceanu, Onofrio & Sadeghpour 2012 ApJ

results of classical trajectory Monte Carlo simulations. Previous results, obtained by Pengelly and Seaton only for dipole-allowed transitions $\ell \to \ell \pm 1$, overestimate the ℓ-changing collisional rate coefficients approximately by a factor of six, and the physical origin of this overestimation is discussed.

- All of the Porter+ work used the Vrinceanu & Flannery formalism

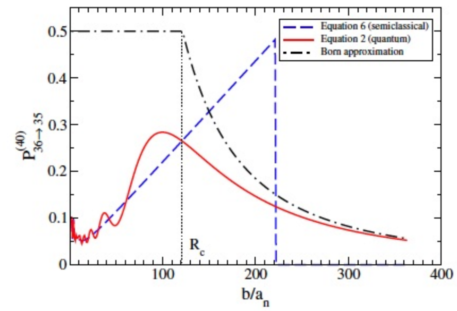


Figure 1. Probabilities for a dipole allowed transition in the $n = 40$ degenerate hydrogen manifold, for a $36 \to 35$ transition, as a function of the scaled impact parameter b/a_n, for a fixed projectile velocity $v = 0.1$ in atomic units, $a_n = n^2 a_0$. Exact quantum probability (red), semiclassical (blue), and Born approximations (black) are compared. The dotted line marks the position of the inner cutoff radius used in the Born approximation in Pengelly & Seaton (1964).

Pete's reply

- Storey & Sochi 2015, MNRAS, 446, 1864

state. The semiclassical approach of Vrinceanu et al. (2012) does not correctly replicate the quantum behaviour at large impact parameter with the probability instead falling discontinuously to zero at a finite and relatively small value of the impact parameter. The missing contribution from large impact parameter is the origin of the order of magnitude difference they report between their results and those of Pengelly & Seaton (1964). We see no reason to prefer their semiclassical result over the quantum treatment at large impact parameters and therefore consider the Pengelly & Seaton (1964) results to be more reliable.

- Pengelly & Seaton got the right answer
- (Vrinceanu don't agree)

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Advance Access publication 2016 April 15

H, He-like recombination spectra – I. *l*-changing collisions for hydrogen

F. Guzmán,[1★] N. R. Badnell,[2] R. J. R. Williams,[3] P. A. M. van Hoof,[4] M. Chatzikos[1] and G. J. Ferland[1]

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[2]Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK
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energy-degenerate states within an *n*-shell. The work of Pengelly & Seaton has, for half-a-century, been considered the definitive study which 'solved' the problem. Recent work by Vrinceanu et al. recommended the use of rate coefficients from a semiclassical approximation which are nearly an order of magnitude smaller than those of Pengelly & Seaton, with the result that significantly higher densities are needed for the *nl* populations to come into local thermodynamic equilibrium. Here, we compare predicted H I emissivities from the two works and find widespread differences, of up to ≈10 per cent. This far exceeds the 1 per cent precision required to obtain the primordial He/H abundance ratio from observations so as to constrain big bang cosmologies. We recommend using the rate coefficients of Pengelly & Seaton for *l*-changing collisions, to describe the H recombination spectrum, based-on their quantum mechanical representation of the long-range dipole interaction.

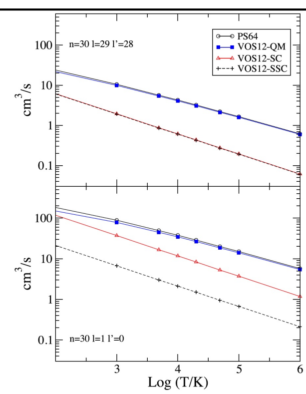
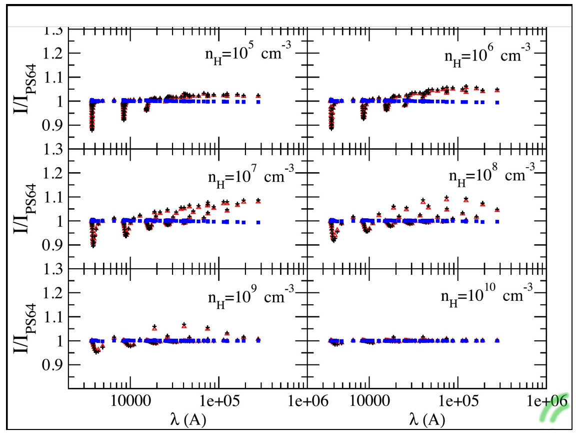


Figure 1. Comparison of *l*-changing collisional rate coefficients for H^++H($n = 30$) collisions at high- and low-*l*. $n_H = 10^4$ cm^{-3}.



MNRAS Advance Access published September 12, 2016

H, He-like recombination spectra II: *l*-changing collisions for He Rydberg states

F. Guzmán[1], N. R. Badnell[2], R. J. R. Williams[3], P. A. M. van Hoof[4], M. Chatzikos[1] and G. J. Ferland[1].
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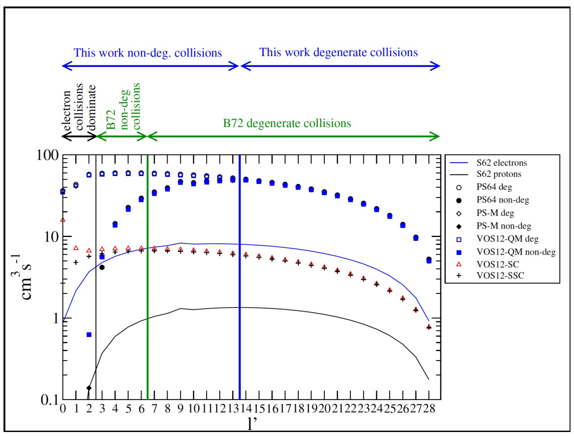
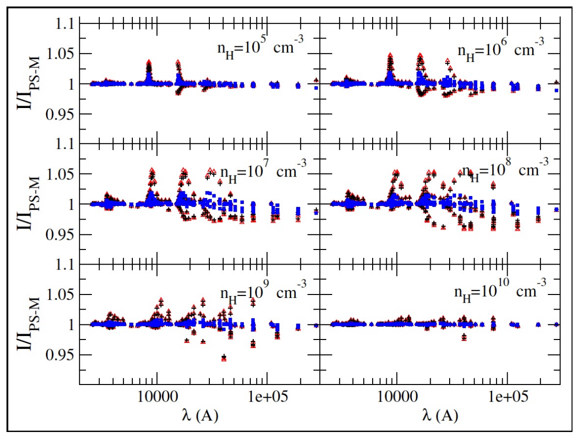
predictions for H I spectra. Here we consider the more complicated case of He atoms, where low-*l* subshells are not energy degenerate. A criterion for deciding when the energy separation between *l* subshells is small enough to apply energy-degenerate collisional theories is given. Moreover, for certain conditions, the Bethe approximation originally proposed by Pengelly & Seaton (1964) is not sufficiently accurate. We introduce a simple modification of this theory which leads to rate coefficients which agree well with those obtained from pure quantal calculations using the approach of Vrinceanu et al. (2012). We show that the *l*-changing rate coefficients from the different theoretical approaches lead to differences of ∼ 10% in He I emissivities in simulations of H II regions using spectral code Cloudy.

Some improvements to P&S

- **We did make modest improvements to P&S**
  - We do not assume that the lower cut off is much lower than the impact parameter. This produces positive rates at low temperatures and high densities
  - We assume a low impact parameter probability that compares better with quantal calculations
  - The modified version is still easy-to-compute and gives very accurate downward transitions compared with the QM method.





Conclusions

- **Precision measurements of Y_p are affected by uncertainties in collision rates among Rydberg levels of H and He**
- **The controversy over *l*-changing collisions introduced a major uncertainty**
  - The vector sum of all this work is the null vector – Pengelly & Seaton 1964 basically got it right
- **Atomic physics is crucial to understanding astronomical spectroscopy**
- **This is an area where tabletop physics can compete with G$ experiments**