Light Elements in the Universe
Proceedings IAU Symposium No. 268, 2009
C. Charbonnel, M. Tosi, F. Primas, & C. Chiappini, eds.

doi:10.1017/S1743921310004011

What is ^{4}He from H II regions? What needs to be done to better understand the systematic errors?

Gary J. Ferland[1], Yuri Izotov[2], Antonio Peimbert[3], Manuel Peimbert[3], Ryan L. Porter[4], Evan Skillman[5] and Gary Steigman[6]

[1]Physics, University of Kentucky, Lexington KY 40506, USA,
email: `gary@pa.uky.edu`

[2]Main Astronomical Observatory, 27 Acad. Zabolotnoho St, UA Kyiv 03680 Ukraine
email: `izotov@mao.kiev.ua`

[3]Instituto de Astronomia, UNAM Apartado Postal 70-264 Mexico 04510, D.F., Mexico,
email: `antonio@astroscu.unam.mx` `peimbert@astroscu.unam.mx`

[4]Astronomy, University of Michigan, Ann Arbor, MI USA
email: `ryanlporter@gmail.com`

[5]Dept. of Astronomy, U of Minnesota, 116 Church St. SE, Minneapolis, MN 55455
email: `skillman@astro.umn.edu`

[6]Depts. of Physics and Astronomy, The Ohio State University, Columbus, OH 43210. USA
email: `steigman.1@osu.edu`

Abstract. Here we summarize the discussion that took place after the presentation of papers discussing measurement of abundances from emission lines in H II regions. A cosmological test using ^{4}He is harder than those using the other light elements due to the small dynamic range over which He/H varies for cosmologically interesting parameters. A precision of much better than 1% is needed. This precision challenges both observations and theory. Several of the major uncertainties were identified and methods of improving the accuracy were described.

Keywords. ISM: abundances, HII regions, Galaxy: abundances

---

1. Introduction

Ferland began the discussion with Don Osterbrock's reminder of how hard this problem is. Don's 1961 PASP paper (Osterbrock & Rogerson 1961) was the first to suggest that much of the current helium originated in the creation of the universe. He recounts the events leading to that paper in *The Helium Content of the Universe* (Osterbrock 2009). He concludes with the statement

> I have heard lectures, and seen cosmological papers, in which values of X and Y derived from nebular spectrophotometry are quoted and used to three significant figures. But all the available calculations of the H I and He I emission-line intensities that I know are based on simplified models. . . . The "mean" values may not represent these conditions to high accuracy . . .

From my own personal knowledge, Don thought that there was roughly a 10% error on He/H determinations from emission lines. I also fear that I was the one who gave the talk Don mentions in his review.

We need to identify the error sources that affect He/H determinations in H II regions, quantify their size, and establish priorities for reducing them to the level needed for precision cosmology. There are five broad sources of error – observing methods, correcting for stellar absorption beneath the emission lines, converting emission-line intensities into ionic abundances, converting ionic abundances into total abundances, and, finally, correcting for stellar contributions to the current helium content. These are enumerated in Davidson & Kinman (1985) and Peimbert *et al.* (2003). Unfortunately many of the errors are systematic rather than statistical and so are hard to quantify.

The discussion was organized into small presentations by active researchers. Each discussed what they saw as the major problems and the way to make progress. The session was then opened to the audience. The following summarizes this discussion.

2. Comments by Gary Ferland

Ryan Porter and I have worked on aspects of the physics of helium emission-line formation on the microscopic level. This includes the atomic physics of the line formation and the physical properties of the ionized gas where He I and H I lines form.

Porter *et al.* (2005) revisited the formation of He I lines under the Case B approximation (Osterbrock & Ferland 2006, hereafter AGN3) conditions. We found emissivities that differ by, in some cases, several percent from the previous high-accuracy calculation by Benjamin *et al.* (1999). These were mainly due to the treatment of non-hydrogenic small-l levels where improved atomic data or methods had become available since the publication of Benjamin *et al.* The critical atomic rates, which have significant remaining uncertainties, are the photoionization cross sections (used to get the radiative recombination coefficient from the Milne relation, AGN3) and l-changing collisions for small-l levels.

Porter *et al.* (2009) did an analysis of the error sources that enter into the calculation of the theoretical emissivities. We found that the photoionization cross sections and l-changing collisions for small-l levels introduce a significant uncertainty. Paradoxically, because of how the lines form, the stronger lines, like λ5876, can have the greater uncertainty. An abundance analysis which relies on only a handful of the stronger lines will have a significant error, as much as several percent, introduced by these uncertainties. It must be stressed that this will be a systematic error that will introduce spurious conclusions if the uncertainties in the atomic physics are not taken into account.

The best way to quantify the uncertainties is to carefully examine a bright H II region where many He I lines can be measured. We did this in Porter *et al.* (2007), using one of the deepest published spectra of the Orion Nebula ever obtained. We found that the observational errors, as indicated by line ratios that were set by the atomic physics, were much larger than was given in the original paper. The intensities of 22 of the highest quality He I lines are consistent with an optimized model of the Orion environment and an observational error of 3.8% percent. The strongest He I line, λ5876, a line with one of the larger theoretical uncertainties in the emissivity, was matched to within 6.6%. The conclusion was that the uncertainties were substantially larger than originally estimated.

What to make of this? Don's guess of a 10% uncertainty in He/H may be realistic. My opinion is that we should understand Orion first. This is the brightest and simplest H II region we know of, close to the Earth and predominantly ionized by a single star. The giant H II region 30 Dor should come next. It is the nearest and brightest object that is a close kin to the galaxies used to derive the primordial helium abundance. It would be good if independent data sets could be obtained and compared to form an impartial estimate of the observational errors. Finally high-precision photoionization cross sections and collisional rates are needed to improve the accuracy of the theoretical emissivities.

3. Comments by Yuri Izotov

Underlying stellar absorption is one of the most important systematic effects that should be taken into account for the primordial ^{4}He determination. Recently, Gonzalez Delgado *et al.* (2005) produced evolutionary stellar population synthesis models at high resolution for single stellar populations. These data allows one to take into account properly the underlying hydrogen and helium line absorption in spectra of H II regions. Another important source of systematic errors are collisional and fluorescent enhancements of He I emission lines. Recently, Porter *et al.* (2005) calculated new He I emissivities in the case B approximation using improved radiative and collisional data. However, for the practical use, simple fits of the emissivities including the contribution of the collisional and fluorescent excitation would be very useful.

I think that one or a few bright H II regions are not enough to derive the primordial ^{4}He abundance. The sample should be large enough to reduce the observational uncertainties. In particular, the spectrum of the bright H II region NGC 346 in the Small Magellanic Cloud mentioned by G.Steigman was obtained with a high signal-to-noise ratio. However, this object is extended and serious problems arise with the subtraction of the night sky foreground. Therefore, it is unlikely to reach very good accuracy in the determination of Y for this object. Bright compact sources are more preferable.

Evan Skillman presented a non-parametric method for corrections of the systematics using HeI lines themselves. Potentially, this method could be one of the best for estimation of the systematic errors. However, I am not very happy to see large error bars in Y values, the large spread of points and the absence of a correlation between helium mass fraction and oxygen abundance. Perhaps, some other constraints should be considered to reduce the large error in Y_p. In particular, the electron temperature and electron number density could be derived from the Balmer jump. Furthermore, larger samples could be considered in order to reduce statistical errors.

4. Comments by Antonio & Manuel Peimbert

By considering that the temperature structure of a gaseous nebula can be represented by the average temperature, T_0, and the mean square temperature variation, t^2, it is possible to a second approximation to determine observationally the temperature structure of a gaseous nebula.

For the 5 metal poor extragalactic H II regions, used by Peimbert, Luridiana, & Peimbert (2007) to derive Y_p, they obtained an average $< t^2 >$ of 0.026. With this value they derive $Y_p = 0.2477$, while by adopting $t^2 = 0.00$ they obtain $Y_p = 0.2523$, a difference of 0.0046. This difference is critical for deriving an accurate Y_p value.

What is the evidence in favor of $< t^2 > = 0.026$? The typical t^2 values derived from photoionization models like CLOUDY are in the 0.003 to 0.010 range. Many astronomers, mainly based on photoionization models and the simplicity of the equations for abundance determinations for constant temperature, adopt $t^2 = 0.000$ to derive chemical abundances. We consider that the observations of high quality that provide t^2 values higher than 0.020 are reliable and that the presence of temperature variations has to be considered in the abundance determinations.

To determine T_0 and t^2 you need to combine line intensities that have a different dependence on the electron temperature. There are at least seven methods that have been used in the literature to determine T_0 and t^2. The four most commonly used are: (a) the combination of [O III] collisionally excited lines with O II recombination lines, (b) the combination of [C III] collisionally excited lines with C II recombination lines,

https://doi.org/10.1017/S1743921310004011 Published online by Cambridge University Press

(c) the combination of collisionally excited lines of [O II] and [O III] with the ratio of the Balmer continuum to a Balmer recombination line, and (d) the combination of about 10 He I lines with [O II] and [O III] collisionally excited lines to obtain t^2, N(He I), τ(3889), and Y simultaneously.

There are four well-observed objects where the four methods mentioned above have been used simultaneously, two H II regions and two planetary nebulae: the Orion nebula, 30 Doradus, NGC 5315, and NGC 6543; the derived $< t^2 >$, values for each object are 0.022 ± 0.002, 0.033 ± 0.005, 0.051 ± 0.004, and 0.028 ± 0.005, respectively. For any given object each of the four methods gives a t^2 in agreement with the average value. This result gives a very strong support to each of the methods, and to the existence of large temperature variations in each of these objects.

The presentation by Peimbert, Peimbert, Carigi, and Luridiana, in these proceedings, includes some observational evidence supporting the large t^2 value (0.036) derived for the galactic H II region M17.

5. Comments by Evan Skillman

My main comment was that the current work on He abundances in extragalactic H II regions indicates that the mean temperature (as indicated by the fluxes of the He I emission lines) is significantly lower than the temperature derived from the [O III] lines. This result is significant beyond the determination of the primordial He abundance, as a lower temperature implies higher abundances of the heavy elements in these regions. Since the uncertainty in the temperature in these H II regions is a dominant source of uncertainty, due to the degeneracy between temperature and density in the minimization, it is very important to sort this out.

Izotov *et al.* (2007) justify the assumption of low temperature fluctuations (and thus the suitability of the [O III] temperature) based on agreement between [O III] temperatures and temperatures derived from the Balmer decrement in a sample of blue compact dwarfs. However, deriving electron temperatures from the Balmer decrement is intrinsically difficult and the history of this technique in the literature is not consistent. I consider this question to be the major uncertainty in the determination of helium abundances in individual nebular objects.

6. Comments by Gary Steigman

In my opinion the dominant sources of uncertainty in the helium abundance determinations are systematic, not statistical. Neither the statistical error nor the uncertain extrapolation to zero metallicity limit the accuracy of our current estimate of the primordial helium abundance and the cosmological constraints that follow from it. To illustrate the significance of a concerted observational (and theoretical) effort to limit the systematic errors, I pointed out the value of a few (one!) good helium abundance determinations.

In my invited review talk I noted that if the value of the baryon density parameter inferred from the inferred primordial deuterium abundance is combined with that derived from the WMAP CMB observations, the estimate of the effective number of neutrinos is $N_{\rm eff} = 4.0 \pm 0.7$, which is within 1.4σ of the standard model value of 3. In contrast, if we simply adopt as an **upper limit** to the primordial helium abundance the Peimbert, Luridiana, Peimbert (2007) estimate of the helium abundance (and its uncertainty) for the SMC H II region NGC 346, $Y_{\rm SMC} = 0.2507 \pm 0.0042$ (where their statistical and systematic errors have been added linearly), and combine this with the observationally inferred primordial deuterium abundance, we would find an **upper bound** to the effective

https://doi.org/10.1017/S1743921310004011 Published online by Cambridge University Press

number of neutrinos, $N_{\rm eff\ max} \leqslant 3.2 \pm 0.3$. The key point of this example is to illustrate that if the PLP error estimate is realistic, the **uncertainty** in $N_{\rm eff}$ may be reduced by more than a factor of two. A few more carefully observed and analysed H II regions like NGC 346 could go a long way in pinning down the value of the primordial helium abundance and tightening the constraints that follow from it.

7. Conclusions

The discussion illuminated several sources of uncertainty in the precision analysis of emission lines emitted by H II regions. A variety of approaches were suggested as ways to improve the accuracy of the derived abundances. It would be productive if all were attempted. Gary Steigman's comment that even a very few high-precision measurements would be cosmologically significant established a realizable goal. Clearly much work, both observational and theoretical, remains to be done.

References

Benjamin, Robert A., Skillman, Evan D., Smits, & Derck, P. 1999, *ApJ*, 514, 307

Davidson, K. & Kinman, T. D. 1985, *ApJS*, 58, 321

Gonzalez Delgado, R. M., Cervio, M., Martins, L. P., Leitherer, C., & Hauschildt, P. H. 2005, *MNRAS*, 357, 945

Izotov, Y., Thuan, T., & Stasinska, G. 2007, *ApJ*, 662, 15

Osterbrock, D. E. & Ferland, G. J. 2006 *The Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, 2nd Edition (Mill Valley; University Science Press) (ANG3)

Osterbrock, D. E. & Rogerson, J. B. 1961, *PASP*, 73, 129

Osterbrock, D. E., 2009, in *Finding the Big Bang*, P. J. E. Peebles, L. A. Page & R. B. Partridge eds (Cambridge; Cambridge University Press), p. 86

Peimbert, Manuel, Luridiana, Valentina & Peimbert, Antonio 2007, *ApJ*, 666, 636

Peimbert, Manuel, Peimbert, Antonio, Luridiana, Valentina, & Ruiz, Maria Teresa 2003, *ASPC*, 297, 81

Porter, R. L., Bauman, R. P., Ferland, G. J., & MacAdam, K. B. 2005, *ApJ*, 622, L73

Porter, R. L., Ferland, G. J., & MacAdam, K. B. 2007, *ApJ*, 657, 327

Porter, R. L., Ferland, G. J., MacAdam, K. B., & Storey, P. J. 2009, *MNRAS*, 393L, 36

Roberto Costa

Piercarlo Bonifacio