NATURE September 12, 1964

THE MYSTERY OF THE COSMIC HELIUM ABUNDANCE

By PROF. F. HOYLE, F.R.S., and DR. R. J. TAYLER
University of Cambridge

Question: what was the mystery in 1964?

Hoyle: Carbon via triple alpha reaction, 1952
Burbidge^2, Fowler, Hoyle: s- and r-proc, 1957
Alpher, Gamow: BBNucleosynthesis, >1948
Penzias and Wilson ⇒ ApJ: 13 May, 1965

1977: Observed He abundance (25%) $\Rightarrow N_\nu < 5$

Volume 66B, number 2 PHYSICS LETTERS 17 January 1977

COSMOLOGICAL LIMITS TO THE NUMBER OF MASSIVE LEPTONS

Gary STEIGMAN
National Radio Astronomy Observatory[1] *and Yale University*[2]*, USA*

David N. SCHRAMM
University of Chicago, Enrico Fermi Institute (LASR), 933 E 56th, Chicago, Ill. 60637, USA

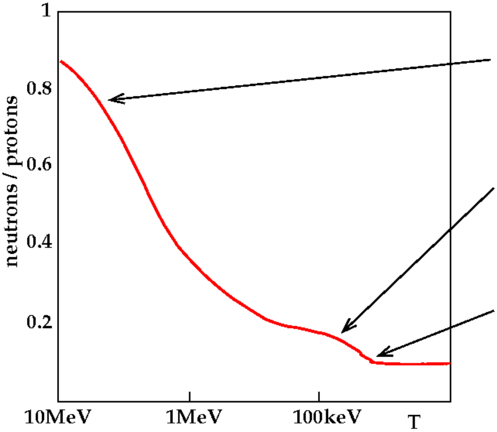
James E. GUNN
University of Chicago and California Institute of Technology[2]*, USA*

Received 29 November 1976

If massive leptons exist, their associated neutrinos would have been copiously produced in the early stages of the hot, big bang cosmology. These neutrinos would have contributed to the total energy density and would have had the effect of speeding up the expansion of the universe. The effect of the speed-up on primordial nucleosynthesis is to produce a higher abundance of ^{4}He. It is shown that observational limits to the primordial abundance of ^{4}He lead to the constraint that the total number of types of heavy lepton must be less than or equal to 5.

PDG: $1.8 < N_\nu < 4.5$ (95%CL) (Cyburt et al., 2005)
PDG: $N_\nu < 16$; (Hoyle & Tayler, 1964)

neutron-proton ratio vs. temperature:



..

thermal equilibrium via
$\nu_e n \leftrightarrow e^- p$

..

$n \rightarrow p e^- \bar{\nu}_e$

nucleosynthesis ($T = 60$keV)
(number of neutrons reduced by decay)

More neutrinos $\Rightarrow$ Faster Expansion
$\Rightarrow$ fewer neutron decays $\Rightarrow$ more He

Hoyle and Tayler, 1964

IT is usually supposed that the original material of the Galaxy was pristine material. Even solar material is usually regarded as 'uncooked', apart from the small concentrations of heavy elements amounting to about 2 per cent by mass which are believed on good grounds to have been produced by nuclear reactions in stars. However, the presence of helium, in a ratio by mass to hydrogen of about 1 : 2, shows that this is not strictly the case. Granted this, it is still often assumed in astro-

Hoyle and Tayler, 1964

> It is the purpose of this article to suggest that mild 'cooking' is not enough and that most, if not all, of the material of our everyday world, of the Sun, of the stars in our Galaxy and probably of the whole local group of galaxies, if not the whole Universe, has been cooked' to a temperature in excess of 10^{10} K. The conclusion is reached that: (i) the Universe had a singular origin or is oscillatory, or (ii) the occurrence of massive objects has been more frequent than has hitherto been supposed.

Hoyle, the Big Bang sceptic, says that "a singular origin" is one of two natural explanations of large He/H.

Hoyle and Tayler, 1964

Table 1

	He/H
Orion nebula (ref. 1)	0·091
NGC 604 in *M* 33 (ref. 2)	0·102
Small magellanic cloud (ref. 3)	0·11
B stars (ref. 4)	0·16
Planetary nebulæ (ref. 5)	0·09–0·19
Solar cosmic rays (refs. 6 and 7)	0·091
Solar evolution (ref. 8)	0·09

Mendez, Thesis, 1964

THE SPECTROPHOTOMETRY OF THE ORION NEBULA

Thesis by

Manuel E. Mendez

In Partial Fulfillment of the Requirements

For the Degree of

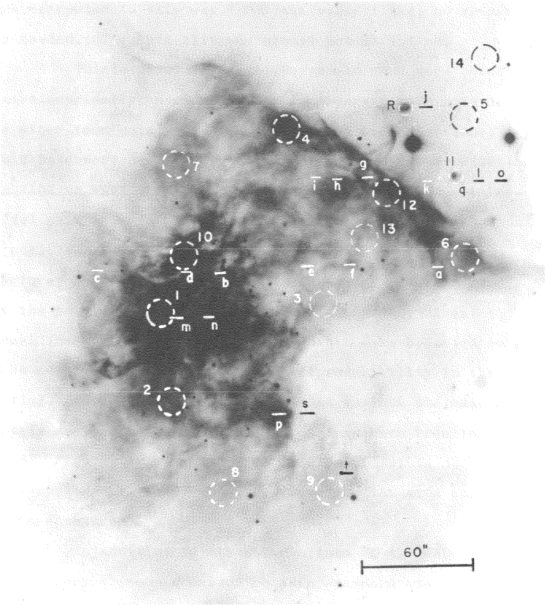
Doctor of Philosophy

California Institute of Technology

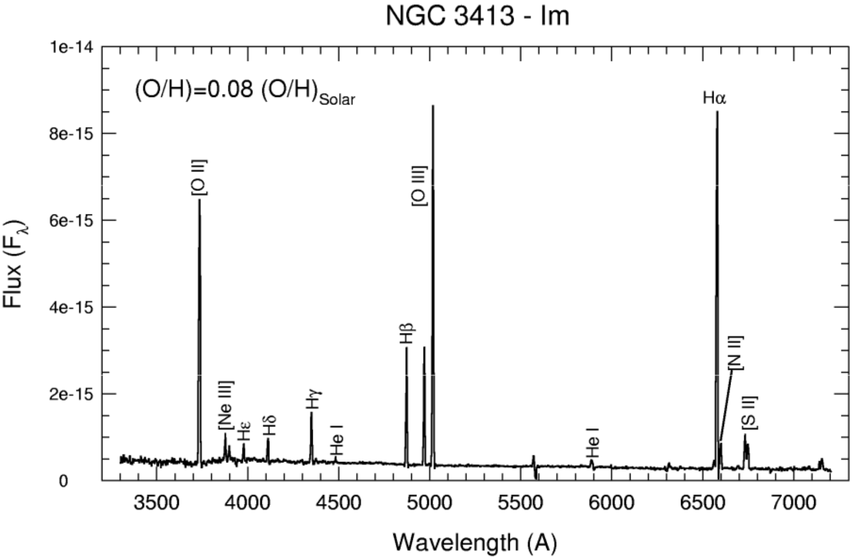
Pasadena, California

1964

Orion Nebula (Mendez thesis)



HII region spectrum



HII region spectrum

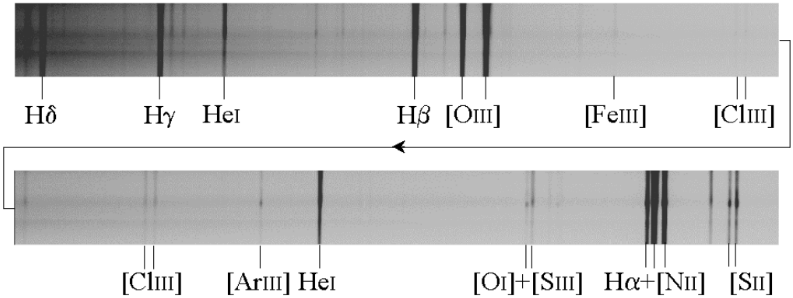


Figure III-11: Long-slit spectrum of the Orion Nebula taken in the region of the "Orion Bar" [1.8m Perkins Telescope, R. Pogge & S.R. Benfer]

HII region spectrum (Mendez)

The spectral range covered photoelectrically from $\lambda 3500$ to $\lambda 11000$ was observed using two photoelectric cells: the 1P21 was used to measure the region from 3600 to 5100; whereas an S-1 photocathode was employed in the range of wavelengths from 4800 to 11000. The tube was the RCA 7102 operating with 1300 volts.

Mendez, Thesis, 1964

due to pure recombination. From the recombination coefficients as given by Burgess, one derives

$$\frac{N(He^{+})}{N(H^{+})} = 0.98\ \frac{I(\lambda 5876)}{I(\lambda 4861)} \qquad (29)$$

and also

$$\frac{N(He^{+})}{N(H^{+})} = 2.41\ \frac{I(\lambda 4471)}{I(\lambda 4861)}$$

Hoyle and Tayler, 1964: Back of the envolope

We begin our argument by noticing that helium production in ordinary stars is inadequate to explain the values in Table 1, if they are general throughout the Galaxy, by a factor of about 10. Multiplying the present-day optical emission of the Galaxy, $\sim 4 \times 10^{43}$ ergs sec^{-1}, by the age of the Galaxy, $\sim 3 \times 10^{17}$ sec, and then dividing by the energy production per gram, $\sim 6 \times 10^{18}$ ergs g^{-1}, for the process H $\rightarrow$ He, gives $\sim 2 \times 10^{42}$ g ($10^9 M_\odot$). This is the mass of hydrogen that must be converted to helium in order to supply the present-day optical output of the Galaxy for the whole of its lifetime. Allowance for emis-

more than ~ 3. Since the total mass of the Galaxy is $\sim 10^{11} M_\odot$ the value of the He/H to be expected from H $\rightarrow$ He inside stars is only $\sim 0{\cdot}01$. While it is true that the Galaxy may have been much more luminous in the past than it is now, there is no evidence that this was the case.

Hoyle and Tayler: Gamow Fine Tunes η!

In the theory of Alpher, Bethe and Gamow[9] the density was given by:

$$\rho \approx 10^{-4} T_{10}^{3} \text{ g cm}^{-3} \qquad (2)$$

a relation obtained from the following considerations. The material is taken at $t = 0$ to be entirely neutrons. At $t \simeq 10^3$ sec, $T_{10} \simeq 0{\cdot}05$, approximately half the neutrons have decayed. If the density is too low the resulting protons do not combine with the remaining neutrons, and very little helium is formed. On the other hand, if the density is too high there is a complete combination of neutrons and protons, and with the further combination of the resulting deuterium into helium very little hydrogen remains as t increases. Thus only by a rather precise adjustment of the density, that is, by (2), can the situation be arranged so that hydrogen and helium emerge in approximately equal amounts.

$\Rightarrow \eta \sim 3 \times 10^{-12}$

Hoyle and Tayler: Effect of Neutrinos

It was pointed out by Hayashi[10] and Alpher, Follin and Herman[11] that the assumption of material initially composed wholly of neutrons is not correct. The radiation field generates electron-positron pairs by:

$$\gamma + \gamma \rightleftarrows e^- + e^+ \tag{3}$$

and the pairs promote the following reactions:

$$n + e^+ \rightleftarrows p + \bar{\nu} \tag{4}$$

$$p + e^- \rightleftarrows n + \nu \tag{5}$$

The situation evidently depends on the rates of these reactions. It turns out that for sufficiently small t the balance of the reactions is thermodynamic. This means that not only are protons generated by (4) and (5), but also that the energy densities of the pairs and of the neutrinos must be included in the cosmological equations. At $T_{10} \simeq 10^2$, even μ-neutrinos are produced and these

Hoyle and Tayler: Limit on $N_\nu < 16$

Before comparing this result with observation we note that variations of the cosmological conditions which led to equation (6) all seem as if they would have the effect of increasing He/H. If the rest mass energy density were not less than the sum of the energy densities of radiation, pairs and neutrinos, the Universe would have to expand faster at a given temperature in order to overcome the increased gravity, the time-scale would be shorter and the coefficient on the right-hand side of equation (12) would be reduced. Similarly, if there were more than two kinds of neutrino the expansion would have to be faster in order to overcome the gravitational attraction of the extra neutrinos, and the time-scale would again be shorter; and the smaller the coefficient on the right-hand side of equation (12) the larger the ratio He/H turns out to be.

Hoyle and Tayler: He production independent of η

Mr. J. Faulkner has solved the equation for several starting temperatures. Provided $T_{10} > 2{\cdot}5$ initially, he finds $n/(n + p) = 0{\cdot}18$ at $T_{10} = 0{\cdot}5$, giving:

$$\frac{\mathrm{He}}{\mathrm{H}} = \frac{n}{2(p - n)} \simeq 0{\cdot}14 \qquad (13)$$

a result in good agreement with the calculations of Alpher, Follin and Herman[11]. Allowing for the approximation in our integration procedure we estimate that this value is not more uncertain than $0{\cdot}14 \pm 0{\cdot}02$. It should be particularly noted that, unlike the result of Alpher, Bethe and Gamow, this value depends only slightly on the assumed material density; essentially this result is obtained provided the density is high enough for deuterons to be formed in a time short compared to the neutron half-life and low enough for the rest mass energy density of the nucleons to be neglected in comparison with the energy density of the radiation field.

Hoyle and Tayler: He abundance $\Rightarrow$Big Bang

It is reasonable, however, to argue in an opposite way. The fact that observed He/H values never differ from 0·14 by more than a factor 2, combined with the fact that the observed values are of necessity subject to some uncertainty, could be interpreted as evidence that the Universe did have a singular origin (or that it is oscillatory). The difficulty of explaining the observed values in terms of hydrogen-burning in ordinary stars supports this point of view. So far as we are aware, there is only one strong counter to this argument, namely, that there is nothing really special to cosmology in the foregoing discussion.

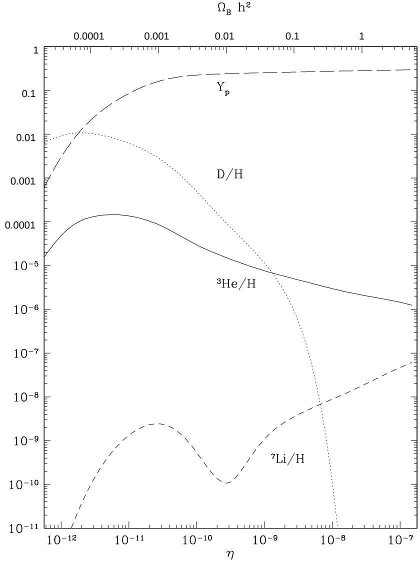
Hoyle and Tayler: η fine tuning replaced with G_F fine tuning!

> more accurately, but we would stress two general points: (1) the weak interaction cross-sections turn out to be just of the right order of magnitude for interesting effects to occur in the time-scale available; (2) for a wide range of physical conditions (for example, nucleon density) roughly the observed amount of helium is produced.

$\Gamma_\nu \sim H$ at $T \sim m_n - m_p$

$$\Rightarrow G_F^2 \Delta m^3 m_{pl} \sim \alpha^2 \Delta m^3 m_{pl} / M_W^4 \sim 1$$

Abundances vs. η



Cooke and Fumagalli, 2018

pendent techniques. Here we report the first determination of the primordial helium abundance based on a near-pristine intergalactic gas cloud that is seen in absorption against the light of a background quasar. This gas cloud, observed when the Universe was just one-third of its present age ($z_{\rm abs} = 1.724$), has a metal content ~ 100 times less than the Sun, and $\gtrsim 30\%$ less metals than the most metal-poor $\rm H\,II$ region currently known where a determination of the primordial helium abundance is afforded. We conclude that the helium abundance of this intergalactic gas cloud is $Y = 0.250^{+0.033}_{-0.025}$, which agrees with the Standard Model primordial value[8–10], $Y_{\rm P} = 0.24672 \pm 0.00017$. Our determination

Cooke and Fumagalli, 2018

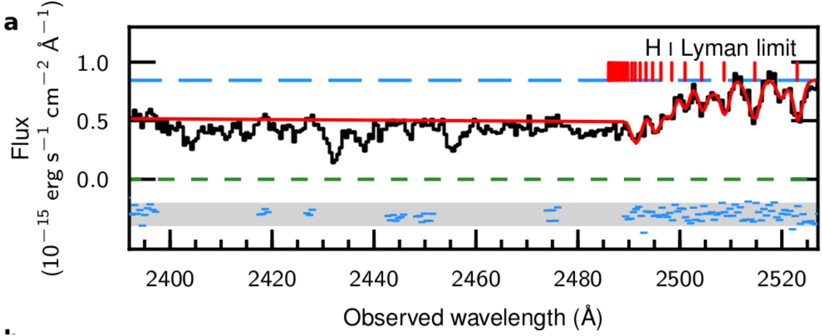
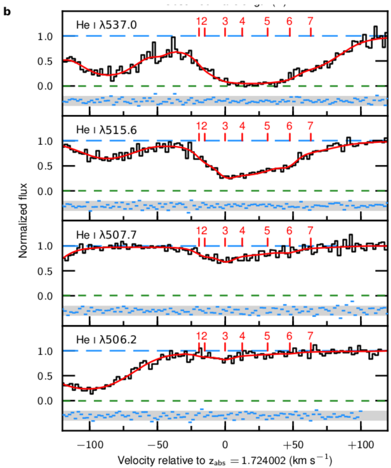


Figure 1 | Hydrogen and helium absorption from an intergalactic gas cloud toward the quasar HS 1700+6416. a, High order H I Lyman series absorption lines (indicated by the red tick marks above the spectrum) and H I Lyman continuum absorption (blueward of an observed wavelength $\lambda \lesssim 2483$Å). The best-fit model is shown by the continuous red curve and the power-law fit to the quasar continuum is shown by the long dashed blue line. **b,** Four He I absorption lines associated with the pLLS at redshift $z_{\rm abs} \simeq 1.724$. The red tick marks and associated numbers above the spectrum indicate the locations of the components comprising the absorption model. The blue points below all spectra are the normalised fit residuals, (data–model)/error, of all pixels that were used in the analysis, and the grey bands represent a confidence



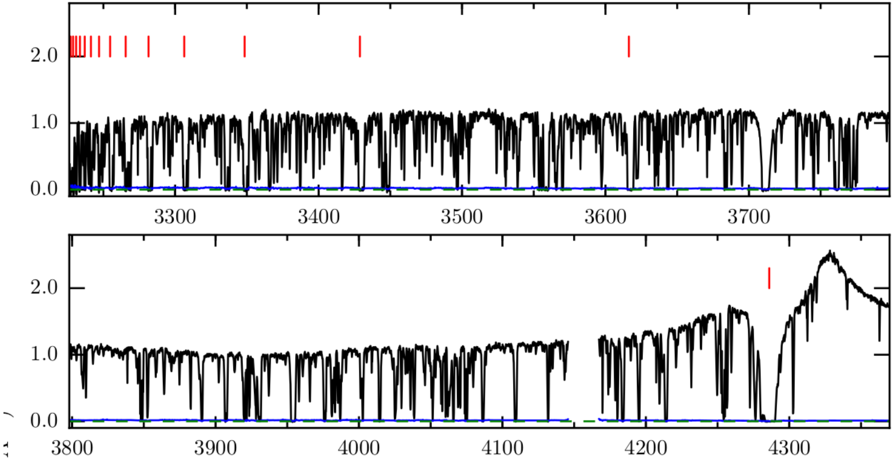
by the long dashed blue line. **b,** Four He I absorption lines associated with the pLLS at redshift $z_{\rm abs} \simeq 1.724$. The red tick marks and associated numbers above the spectrum indicate the locations of the components comprising the absorption model. The blue points below all spectra are the normalised fit residuals, (data–model)/error, of all pixels that were used in the analysis, and the grey bands represent a confidence interval of $\pm 2\sigma$. Labels at the top of all panels indicate the transition shown.

Cooke et al, 2017: One Percent Determination of the Primordial Deuterium Abundance

ABSTRACT

We report a reanalysis of a near-pristine absorption system, located at a redshift $z_{abs} = 2.52564$ toward the quasar Q1243+307, based on the combination of archival and new data obtained with the HIRES echelle spectrograph on the Keck telescope. This absorption system, which has an oxygen abundance [O/H]=-2.769 ± 0.028 ($\simeq 1/600$ of the solar abundance), is among the lowest metallicity systems currently known where a precise measurement of the deuterium abundance is afforded. Our detailed analysis of this system concludes, on the basis of eight D I absorption lines, that the deuterium abundance of this gas cloud is $\log_{10}(\mathrm{D/H}) = -4.622 \pm 0.015$, which is in very good agreement with the results previously reported by Kirkman et al., but with an improvement on the precision of this single measurement by a factor of ~ 3.5. Combining this new estimate with our previous sample of six high precision and homogeneously analyzed D/H measurements, we deduce that the primordial deuterium abundance is $\log_{10}(\mathrm{D/H})_\mathrm{P} = -4.5974 \pm 0.0052$ or, expressed as a linear quantity, $10^5(\mathrm{D/H})_\mathrm{P} = 2.527 \pm 0.030$; this value corresponds to a one percent determination of the primordial deuterium abundance. Combining our result with a big bang nucleosynthesis (BBN) calculation that uses the latest nuclear physics input, we find that the baryon density derived from BBN agrees to within 2σ of the latest results from the *Planck* cosmic microwave background data.

Cooke et al, 2017



Cooke et al, 2017