The discovery of oxygen in the Universe

Grażyna Stasińska
The discovery of oxygen

**Carl Scheele (1742-1786)**

is the first (1773;1777) to isolate oxygen by heating HgO he found that it released a gas which enhanced combustion.

**Joseph Priestley (1733-1804)**

was the first (1774) to publish this result (which he interpreted within the phlogiston theory)

**Antoine de Lavoisier (1743-1794)**

discovered that air contains about 20 % oxygen and that when any substance burns, it actually combines chemically with oxygen (1775) he gave oxygen its present name (oxy-gen = acid-forming) he stated the law of the conservation of matter

**Georg Ernst Stahl (1659-1734)**

the father of the phlogiston theory. phlogiston is the fire that escapes from matter when it burns
Before the “discovery” of oxygen

Leonardo da Vinci (1452-1519)
- air is a mixture of gases
- breathing ~ combustion
"Where flame cannot live no animal that draw breath can live."

Michael Sendivogius (1566-1636) (Michał Sędziwój)
produced a gas he called “food of life”
by heating saltpeter (KNO₃)

Cornelius Drebbel (1572-1633)
constructed in 1621 the first submarine.
To “refresh” the air inside it, he generated oxygen by heating saltpeter as Sendivogius had taught him.
“chemistry” before Lavoisier

Anaxagoras of Clazomenes (500 BC - 428 BC)
had already expressed “the law of Lavoisier”:
“Rien ne se perd, rien ne se crée, tout se transforme”

Robert Boyle (1627-1691)
• noted that it was impossible to combine
the four Greek elements to form any substance
• he called element any substance
that cannot be decomposed into a simpler substance
From the molecule to the atom

John Dalton (1766-1844)
- Elements are made of very small particles:
- Atoms of a given element are identical in size, mass, and other properties;
- Atoms of different elements combine in simple whole-number ratios to form chemical compounds

Stanislao Canizzarro (1826-1910)
At the first international chemical congress (Karlsruhe 1860) he emphasized the difference between atoms and molecules

Dimitri Mendeleev (1834-1907)
- classified the 63 elements known by their atomic weights, organizing them into groups with similar properties.
- predicted the properties of elements yet to be discovered.
Oxygen on Earth

- Oxygen constitutes 49.2% of the Earth’s crust by mass (Si O$_2$).
- Oxygen constitutes 88.2% of the mass of the Oceans (H$_2$O).
- Oxygen gas constitutes 23.1% of the Earth’s atmosphere by mass (O$_2$).
Oxygen in meteorites

Jean-Baptiste Biot (1774-1862)

the origin of meteorites is extraterrestrial (1803)

meteories contain silicium, iron, megnesium .. and oxygen

météorite de l’Aigle
Oxygen in the Sun?

Wollaston 1802
first spectrum of the Sun

Fraunhofer 1814
first systematic study of the absorption lines

Kirchhoff & Bunsen 1860-1861
Fraunhofer lines have same wavelengths as some heated metals

1863:
the Sun’s atmosphere contains hydrogen, sodium, iron, magnesium.

what about oxygen?
Oxygen in the Sun?

1877Natur..17..161M Meldola, R. Oxygen in the Sun
1878Obs.....1..286D Draper, H. Discovery of oxygen in the sun
1878MNRAS..38..201D Draper, H. Prof. H. Draper's researches on the existence of oxygen in the Sun
1878Natur..17..339D Draper, Henry Oxygen in the Sun
1878Obs.....1..315S Schuster, A. On the presence of oxygen in the sun
1878Natur..18..654. On the Presence of Dark Lines in the Solar Spectrum which Correspond Closely to the Lines of the Spectrum of Oxygen
1879AReg...17..117D Draper, Henry. Correspondence - Oxygen in the Sun.
1879AReg...17..117R Ranyard, A. C. Correspondence - Oxygen in the Sun.
1879MNRAS..39..388S Schuster, A. on the probable presence of oxygen in the solar chromosphere
1879MNRAS..39..440D Draper, H. on the coincidence of the bright lines of the oxygen spectrum with bright lines in the solar spectrum
1879Obs.....3..46D Draper, J. C. On the dark lines of oxygen in the solar spectrum on the less refrangible side of G
1879Obs.....3..118M Maunder, E. W. Bright lines of oxygen in the solar spectrum
1879MNRAS..40...14D Draper, J. C. on a photograph of the solar spectrum, showing dark lines of oxygen

all these are false detections!
The first detection of oxygen in the Sun

Runge & Paschen 1896

The O I 7777 lines are weak and in a spectral zone not much studied before.
The detection of oxygen in stars

Solar-like stars
only a few other OI lines were later identified in the Sun and solar-like stars.

hot stars
McClean 1897, Gill 1899
detection of lines of ionized oxygen

ON THE PRESENCE OF OXYGEN IN THE ATMOSPHERES OF CERTAIN FIXED STARS.

By David Gill.

In a paper read before the Society on April 8, 1897, and in a subsequent paper, Mr. Frank McClean draws attention to the grouping of lines other than those of helium and hydrogen in the spectra of β Scorpii, β Canis Majoris, β Centauri and β Crucis, suggesting that the close correspondence between the grouping of these extra lines and the known lines of oxygen, points to the probable presence of that gas in the atmosphere of these stars.
The first determination of elemental abundances in stars

Cecilia Payne (1900-1979)
• her thesis (1925) lays the basis of quantitative analysis of stellar spectra:
• intensities of abssorption lines are complicated function of temperature, pressure and atomic data.
• weak lines do not necessarily indicate small abundances

<table>
<thead>
<tr>
<th>Element</th>
<th>Stellar Abundance</th>
<th>Terrestrial Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>45</td>
<td>54</td>
</tr>
<tr>
<td>Silicon</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Sodium</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Calcium</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>Iron</td>
<td>2.5</td>
<td>1</td>
</tr>
</tbody>
</table>

The derived “relative abundance” for the stellar atmosphere places oxygen at the head of the elements, with about thirty times as many atoms as calcium.
The first determination of elemental abundances in stars

What about hydrogen?

Hydrogen and helium are omitted from the table. The stellar abundance deduced for these elements is improbably high, and is almost certainly not real. Russell and Compton\textsuperscript{17} have suggested that the anomalous astrophysical behavior of the Balmer lines may be attributed to metastability, an interpretation which would also explain the great apparent abundance of the element in stellar atmospheres. The abundance of

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance of atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stellar</td>
</tr>
<tr>
<td>Oxygen</td>
<td>45</td>
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<tr>
<td>Silicon</td>
<td>16</td>
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<tr>
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<td>3</td>
</tr>
<tr>
<td>Iron</td>
<td>2.5</td>
</tr>
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</table>
The first solar oxygen abundance

Henry Norris Russell
(1877-1957)

1929

<table>
<thead>
<tr>
<th>Element</th>
<th>By Volume</th>
<th>By Weight</th>
<th>log T</th>
<th>log Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>60 parts</td>
<td>60</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Helium</td>
<td>2</td>
<td>8?</td>
<td>8.4?</td>
<td>9.0?</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2</td>
<td>32</td>
<td>8.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Metals</td>
<td>1</td>
<td>32</td>
<td>8.1</td>
<td>9.6</td>
</tr>
<tr>
<td>Free electrons</td>
<td>0.8</td>
<td>0</td>
<td>8.0</td>
<td>......</td>
</tr>
<tr>
<td>Total</td>
<td>65.8</td>
<td>132</td>
<td>......</td>
<td>......</td>
</tr>
</tbody>
</table>
The detection of nebulium

William Huggins obtains the first spectrum of a PN (1863)

Padre Angelo Secchi, obtains the first spectrum of the Orion nebula (1864)

oxygen lines were very strong in both but they were attributed to nebulium
Oxygen in nebulae

Bowen (1898-1973)

1927: the lines attributed to « nebulium » are due to forbidden transitions of oxygen, not observable on earth.

1934: oxygen lines in nebulae have intensities similar to hydrogen lines not because the abundances of the two elements are similar but because oxygen possesses energy levels that are easily attained by collisions with electrons.

Lawrence Aller (1913-2003)
Donald Menzel (1901-1976)

1945: method to compute nebular abundances
Where does the oxygen come from?
The first steps in the quest of the origin of the elements

Rutherford 1900

The mass of the atoms mostly resides in a small nucleus composed of protons and neutrons

Soddy & Rutherford 1901

Radioactive thorium transforms into radium
This is transmutation (= nuclear reaction)

The idea that atoms were « genetically connected » was in the air.
Thinking of stars

Rutherford (1907)
radioactive dating of terrestrial rocks shows that the Earth is at least one billion year old, therefore the Sun should also be that old.

Russell (1919)
If stars were shining only due to gravitational contraction, their lifetime would be about 1 million years. Thus another source of energy must be present in stars.

Jeans (1907)
A star contracting under its own gravity reaches a temperature of about 1 million degrees.

Atkinson & Houtermans (1929)
At such temperatures, some nuclear fusion reactions can occur and generate energy.

Atkinson (1931) Is the first to suggest that stellar nucleosynthesis is the main energy source in stars and that it transforms the simplest atoms into more complex ones by subsequent addition of protons.
How elements are produced in the stars

In fact, Atkinson’s model proved not entirely correct

Burbidge, Burbidge, Fowler et Hoyle (1957, B2FH)
Describe in detail all the nuclear reactions in stellar interiors.

In particular
The production of oxygen
The chemical evolution of the Universe

Burbidge, Burbidge, Fowler et Hoyle (1957,B2FH)

In this same paper they also predict that
During the course of their lives
Stars may loose matter
And even explode

Thus progressive enriching the Universe in heavy elements,
In particular oxygen.

Successive generations of stars in galaxies will have their atmospheres each time richer in heavy elements
The first models of the chemical evolution of galaxies

1971 Cameron

1971 Searle
Os ciclos estelares

**estrela de pequena massa** | **estrela de grande massa**
---|---
**gigante vermelha** | **supergigante vermelha**
**nebulosa planetária** | **supernova**

anã branca | estrela de neutrons ou buraco negro

**o ciclo leva um bilhão de anos** | **o ciclo leva 10 milhões de anos**

- Parte dos elementos recém-formados são **jogados no meio interestelar** e **enriquescem** as futuras gerações de estrelas
- Outra parte fica **preso para sempre** nos remanentes de estrelas
- O **oxigênio que vemos nas galaxias** vem só das estrelas de **grande massa**
The $^{12}\text{C} \left(\alpha, \gamma\right) ^{16}\text{O}$ reaction

The “holy grail” of nuclear astrophysics (W. Fowler) and most studied nuclear reaction both theoretically and experimentally is not even known to within a factor of two!

Illustrations from presentation by Rehm
And what the measurement of oxygen abundances in celestial objects?

Not easy in general

But progress is being made

Although many questions are still under debate

A few examples follow…
The abundances of oxygen in the Sun in units of $12 + \log O/H$:

<table>
<thead>
<tr>
<th>Author</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payne 1925</td>
<td>8</td>
</tr>
<tr>
<td>Russell 1929</td>
<td>9.5</td>
</tr>
<tr>
<td>Hunaerts 1947</td>
<td>9.23</td>
</tr>
<tr>
<td>Bowen 1948</td>
<td>8.2</td>
</tr>
<tr>
<td>Unsold 1948</td>
<td>8.73</td>
</tr>
<tr>
<td>Class 1950</td>
<td>8.65</td>
</tr>
<tr>
<td>Goldberg 1960</td>
<td>8.96</td>
</tr>
<tr>
<td>Lambert 1968</td>
<td>8.77</td>
</tr>
<tr>
<td>Nikolaides 1973</td>
<td>8.93</td>
</tr>
<tr>
<td>Lambert 1978</td>
<td>8.92</td>
</tr>
<tr>
<td>Anders Grevesse 1989</td>
<td>8.93</td>
</tr>
<tr>
<td>Grevesse Sauval 1998</td>
<td>8.83</td>
</tr>
<tr>
<td>Allende Prieto 2001</td>
<td>8.69</td>
</tr>
<tr>
<td>Asplund 2009</td>
<td>8.69</td>
</tr>
<tr>
<td>Caffau Ludwig 2011</td>
<td>8.76</td>
</tr>
</tbody>
</table>

The present day estimate of the solar metallicity is $Z = 0.0134$
(much lower than the canonical value of $Z = 0.02$
and lower than the widely used $Z = 0.0189$ of Anders & Grevesse 1989)
Oxygen abundance determination in hot stars have largely improved thanks to an accurate determination of the 4 important parameters with a self-consistent spectroscopic method.

Simon-Diaz 2009
summary on the oxygen abundance in the solar vicinity

- The height of each rectangle corresponds to the observed dispersion.
- In the center of each rectangle, the dot and the error bar give the average value of A(O) for the considered sample and the typical intrinsic uncertainty in A(O) in each object.
is the observed pattern in agreement with expectations?

Stars: young stars should have a higher $A(O)$ than old stars (Sun, solar analogs, late type giants, Cepheids), due to chemical enrichment. This is not what is seen.

- the Sun was born at a smaller galactocentric radius (but not all the old stars!)
- systematic errors in the oxygen abundances in young or old stars
- recent infall of low metallicity gas in the solar vicinity

Diffuse ISM: $A(O)_{\text{diffuse ISM}} = A(O)_{\text{B-type stars}} - 0.16$.

- needs 30% depletion into dust. Impossible for classical grains (Fe, Mg, Si oxydes)
- Ice?

HII regions:

- using CEL: $A(O)_{\text{HII}} < A(O)_{\text{B-type stars}}$ and depletion in dust cannot account for that
- using RL: one has to explain why $A(O)_{\text{HII}} = A(O)_{\text{diffuse ISM}} + .23$

PNs: Taking into account depletion unto dust grains,

- $A(O)$ from CEL is compatible with solar analogs and late-type stars,
- while $A(O)$ from RL is not.
Oxygen abundance gradients in the Milky Way
The Magellanic Clouds

MW

LMC

SMC
The discrepancy between O/H in H II regions (from CEL) and in B-type stars is seen only in the MW (solar vicinity).

• Does this mean that it is due to a larger depletion of oxygen into dust in the more metal-rich solar vicinity environment?
• Or that the bias in abundance determination from collisionally excited lines disappears at lower metallicities?

None of the two interpretations seems correct.
• There are not enough metals available to deplete oxygen sufficiently to bring HII regions and young stars determinations into agreement.
• On the other hand, the ORL/CEL discrepancy is the same in Magellanic Clouds HII regions as in the MW ones.

Supergiants and Cepheids have the largest A(O) in all three galaxies
The mass-metallicity relation

Tremonti et al 2004

Galaxies from the SDSS DR4

oxygen abundances derived by comparison with a model grid

important bias due to inadequacy of the grid (the assumed N/O vs O/H relation) and the use of $\chi^2$ to choose the best model, as shown by Yin et al 2007
the mass-metallicity relation using different strong line indices

Kewley & Ellison 2008

If a sample of objects has different structural properties than the sample used to calibrate the metallicity indicators, the abundances will be biased.

In the case of massive galaxies, the SDSS spectra are taken through a fibre, which will sample

• the central parts of galaxies if the angular size of the galaxy is large.
• the entire galaxy (HII regions of different metallicities and diffuse ionized gas) If the angular size is small

nb: the dispersion seen when the oxygen abundance is obtained with a direct Te-method is due to the fact that the objects are giant HII regions in spiral galaxies
the form and evolution of the mass metallicity relation

While there is no doubt that a strong M-Z correlation exists extending over 5 decades in stellar masses, the exact form of this correlation is not well-known.

When going to higher redshifts and trying to establish a possible redshift evolution of the M-Z relation, the abundance calibrations must be discussed in detail:

- it is not sufficient to use the same calibrations for samples at different redshift.
- one must make sure that the physical conditions in the emission-line nebulae (ionising radiation field, gas density distribution) are similar,
- or account for any systematic difference.
redshift evolution of the mass-metallicity relation

Savaglio et al 2005

symbols:
Metallicity as a function of galaxy mass for galaxies at \( z \sim 0.7 \). GDDS (black) and CFRS (red) O/H is derived using the R23 index as calibrated by Kobulnicky & Kewley (2004)

green dashed line and hatched area:
“converted” polynomial fit and ±1 σ dispersion, for the SDSS \( z \sim 0.1 \) galaxies (Tremonti et al., 2004)

Most of the \( z \sim 0.69 \) galaxies are distributed below the SDSS fit.
evolution of the mass-metallicity relation using the fossil record of stellar populations in local galaxies

Vale Asari et al 2009
The oxygen abundances in luminous infrared galaxies

They do not follow the general mass-metallicity relation of galaxies

Is this true? (and then could be explained by metallicity dilution resulting from inflows of metal-poor gas from the outer disk to the galaxy central regions (di Matteo et al)

Or is this a mere illusion due to incorrectly estimated abundances?