THE ORION NEBULA AND THE SUN AS PROBES OF GALACTIC CHEMICAL EVOLUTION

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ABSTRACT. The solar and the Orion nebula chemical abundances are discussed; their chemical compositions differ at least in the O/H, He/O and $^{12}C/^{13}C$ ratios. A review of processes that could be responsible for these differences is presented.

1. INTRODUCTION

The Orion nebula and other H II regions have been used, through their chemical composition, to study the chemical evolution of galaxies (i.e. Pagel and Edmunds 1981, Shaver *et al.* 1983). The Sun and other stars have also been used to study the chemical evolution of the galaxy (i.e. Tinsley 1980, Twarog 1980). I thought that a comparison of the chemical composition of the Orion nebula and the Sun could shed some light into the accuracy of the abundance determinations and into the reliability of using H II regions or stars to study the chemical evolution of galaxies. The advantages of studying the chemical composition of the Orion nebula are that we can determine the gaseous abundances of the six most abundant elements in the solar vicinity (H,He,C,N,O and Ne), that the physics that govern the emission lines of these elements is well known, and that we are looking at the chemical composition of the whole object. Alternatively the advantages of studying the Sun are that we can determine accurate abundances for elements that could be partially locked up in dust grains in gaseous nebulae as well as of elements that are very scarce and consequently produce very weak emission lines in gaseous nebulae; the main disadvantage is that the abundances refer to the present photosphere and do not necessarily correspond to the original abundances at the time the Sun was formed.

The Sun and the Orion nebula are not specially peculiar in their chemical abundances with respect to similar objects (e.g. Twarog 1980, Peimbert 1979, Shaver *et al.* 1983). Therefore, if they show any differences in their chemical abundances these differences should be the product of very general processes.

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2. CHEMICAL COMPOSITION OF THE ORION NEBULA AND THE SUN

We will consider mainly those elements which have accurate abundance determinations from observations of the Orion nebula. The abundances are presented in Table I. In what follows we will discuss the accuracy and the relevance of the various determinations.

2.1 Oxygen

In Table I we present the O determinations of three different groups for the Orion nebula. O is the best observed heavy element and I estimate the error to be of 0.06 in the logarithm (0.06 dex). The differences among the three groups for $t^2 = 0.00$ are very small indicating that the internal errors are also very small; t^2 is a measurement of the temperature variations over the observed volume, $t^2 = 0.00$ corresponds to a constant temperature. By comparing temperatures derived by various methods I recommend $t^2 = 0.02$. For the solar value Lambert (1978) estimates an uncertainty of 0.1 dex.

There are three effects that have to be evaluated before a comparison between the Sun and the Orion nebula is made: a) the difference in age, b) the fraction of oxygen trapped in dust grains in the Orion nebula, and c) the difference in galactocentric distance.

The metallicity of the disk has been increasing with time; the difference in Fe/H between the stars being formed now and those formed 4.5×10^9 years ago is of ~ 0.13 dex (Twarog 1980). By assuming that the interstellar medium (ISM) O/H ratio increases like the Fe/H ratio the solar value should be increased by $\sim$ 0.13 dex.

TABLE I. Chemical Abundances*

Element	Orion Nebula				Sun
	$t^2 = 0.00$	$t^2 = 0.00$	$t^2 = 0.00$	$t^2 = 0.02$	
He	...	...	11.02	11.01	10.93
C	8.38	...	8.35	8.57	8.67
N	7.61	7.51	7.57	7.68	7.99
O	8.49	8.49	8.52	8.65	8.92
Ne	7.74	7.70	7.66	7.80	8.03:
S	6.97	6.93	6.97	7.10	7.23
Ar	6.53	6.41	6.60	6.65	6.69:
Y	...	...	...	0.280	0.25
$^{12}C/^{13}C$	...	...	...	...	89±2
Source	1	2	3-5	3-5	6-10

* Where $^{12}C/^{13}C$ is given by number, Y by mass and all the other elements in log N(X) with H = 12.

1. Mathis 1985, 2. Shaver *et al.* 1983, 3. Peimbert and Torres-Peimbert 1977, 4. Torres-Peimbert *et al.* 1980, 5. Peimbert 1983, 6. Gough 1983, 7. Lambert 1978, 8. Lambert and Luck 1978, 9. Meyer 1985a, 10. Boato 1954.

The Orion nebula values presented in Table I correspond to the gaseous phase only. Mc Call (1979) has suggested that the difference in

O/H between the Sun and the Orion nebula probably is due to the large fraction of O embedded in dust grains. Nevertheless the presence of a dust hole in the center of the Orion nebula together with the lack of abundance gradients across the face of the nebula argue against the idea that a large fraction of the heavy elements is trapped in dust grains (Peimbert 1983). Moreover the relative ratios of C, N,O and S with respect to Ne that is not expected to be in dust grains, are close to solar implying that the fraction of each of these elements embedded in dust grains is not large. From the assumption that about 15% of O is locked in Silicate cores and about 5% ± 5% could be locked in polymer mantles (Meyer 1985a) it follows that the O/H ratio in Orion should be increased by about 0.08±0.02 dex.

From the Sun's peculiar motion, with $(u,v,w) = (-9,12,7)$ km s^{-1} (Delhaye 1965) and adopting a solar galactocentric distance of 10 kpc at present, it is obtained that the galactocentric distance of the solar orbit is comprised between 9.9 and 11.6 kpc with an average value of 10.8 kpc (Contopoulos and Strömgren 1965; Martos 1985). The Orion nebula is located at 10.4 kpc from the galactic center (e.g. Sharpless 1952); by assuming that the Sun was formed at its average galactocentric distance and by adopting an O/H gradient of -0.08 dex per kpc (Peimbert 1979, Shaver *et al.* 1983) we would expect an O/H value 0.03 dex higher for Orion than for the Sun. A similar result is obtained if it is assumed that the Sun is at 8 kpc from the galactic center.

Taking the three effects together the O/H difference of 0.25 dex would be increased to 0.33 dex.

Another argument that supports the idea that the photospheric O/H value in the Sun is higher than in the ISM is the fact that Cepheids and related supergiants are deficient by $\sim$ 0.2 dex in O/H relative to the Sun, although other explanations for such difference could be possible (Luck and Lambert 1985).

2.2 Helium

The He/H abundance ratio for the Orion nebula is very accurate with an estimated error smaller than 0.04 dex.

There are no reliable direct determinations of the solar helium abundances. Models of the solar interior and observations of the five-minute high degree and low degree oscillation frequencies yield Y values in the 0.23 to 0.27 range (e.g. Shibahashi *et al.* 1983, Ulrich and Rodes 1983, Noels *et al.* 1984). Based on the solar oscillations and other considerations, Gough (1983) suggests for the protosolar helium abundance, $Yp\odot$, a value of 0.25±0.02?. It should be mentioned that the frequencies predicted by the models do not yet agree with the observed ones implying that this method of determining $Yp\odot$ is still uncertain.

From observations of Jupiter,it has been found that $0.17 < Y < 0.24$ (Gautier 1983). This value might be representative of the primitive solar nebula. It has been argued that the effect of gravitational settling could affect this determination, nevertheless the effect is expected to be smaller than 0.05 in Y. From the previous discussion and following Gough (1983,1985) we will adopt $Yp\odot = 0.25\pm0.02$.

2.3 C/O and $^{12}C/^{13}C$

The accuracy of the gaseous C/O ratio in the Orion nebula is ∿ 0.15 dex, this can be estimated by comparing the determinations by Torres-Peimbert *et al.* (1980) and Perinotto *et al.* (1980) which are in excellent agreement (see also Table I). Some uncertainty is introduced by the possibility that fractions of C and O might be trapped in dust grains, but as mentioned in §2.1 we expect the effect to be very small. The accuracy of the photospheric value is about 0.1 dex or better (Lambert 1978).

The value of $^{12}C/^{13}C$ for the solar system was obtained from meteorites (Boato 1954) and is in very good agreement with the value of 90±15 obtained from CO solar observations (Hall, Noyes and Ayres 1972).

The $^{12}C/^{13}C$ value by Hawkings *et al.* (1984,1985) was obtained from observations of CH^+ in the visual range and is in fair agreement with the average value of 60±8 derived from radiobservations of other molecules (Wannier 1980). The value by Hawkings *et al.* corresponds to the solar vicinity and in what follows we will assume that it is representative of the Orion nebula value.

2.4 Ne/O and Ar/O

There are no determinations of the Ne and Ar values for the solar photosphere. The solar Ne/O and Ar/O values were obtained from the compilation by Meyer (1985a) for solar energetic particles and have an accuracy of about 0.2 dex. The solar values seem to be deficient relative to those of the Orion nebula by 0.04 and 0.23 dex respectively but if we assume an 0.08 dex correction for the O embedded in dust grains the differences change to +0.04 and -0.15 dex.

3. DISCUSSION

In Table II we present a summary of the abundance differences discussed in §2. We have listed five abundance ratios (counting Ne/O and Ar/O as one).

TABLE II. Abundance Difference between the Sun and the Orion Nebula* and a Summary of Possible Explanations.

Explanations	[O/H]	[He/O]	[C/O]	$[^{12}C/^{13}C]$	[Ne,Ar/O]
	+0.3±0.1	-0.4±0.1	-0.2±0.15	+0.3±0.04	-0.1±0.2
Errors (1)	NO	NO	?	NO	?
GCE (2)	NO	NO	YES	YES	NO
SN (3)	YES	YES	YES	YES	NO
Accretion (4)	YES	YES	YES	NO	YES
Solar Wind	YES	NO	?	NO	?

* Given in $[A/B] \equiv \log (A/B)_{\odot} - \log (A/B)_{ORION}$.

1. Errors in: Atomic Physics, Observations, Interpretation.

2. Galactic Chemical Evolution. 3. SN (MESF, ISM abundance fluctuations).

4. Accretion of comets and planetesimals.

The differences for O/H, He/O and $^{12}C/^{13}C$ are substantially higher, for C/O marginally higher and for (Ne,Ar)/O smaller than the estimated errors. The five ratios behave differently under various hypotheses that have been advanced to explain: abundance anomalies in the solar system and the neutrino solar experiment. In what follows we will analyze the consequences of some of these hypotheses.

3.1 Galactic Chemical Evolution

We have already considered the effect of GCE on the O/H ratio, but not on the other ratios. In Figure 1 we show a Y *versus* O/H diagram where very accurate abundance determinations for galactic and extragalactic H II regions are presented (Peimbert and Torres-Peimbert 1974,1976,1977, 1986; Peimbert *et al.* 1986) together with the solar value from Table I. The objects with higher gaseous content are those with the smallest O/H and Y values; simple models of galactic chemical evolution predict that as

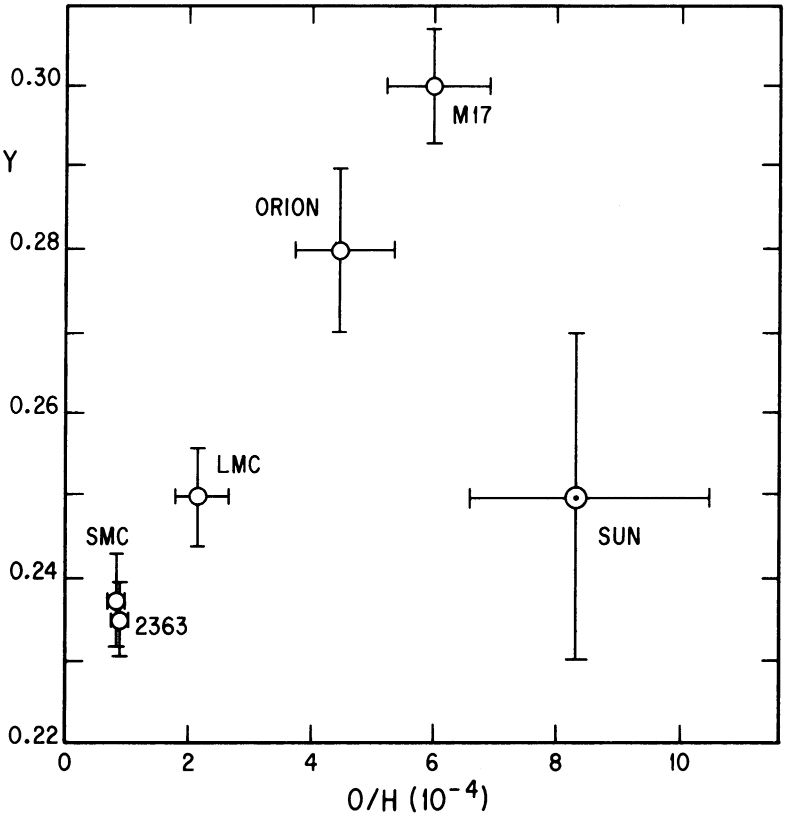

Figure 1. Helium *versus* O/H diagram for galactic H II regions (the Orion nebula and M17), extragalactic H II regions (the Small Magellanic Cloud, the Large Magellanic Cloud, and NGC 2363), and the Sun.

the gaseous amount is exhausted, Y and O/H increase (e.g. Serrano and Peimbert 1981). The H II regions delineate a GCE trajectory in the Y *versus* O/H diagram and the Sun is well out of it. To be on the GCE trajectory the solar O/H value has to be smaller by a factor of four or the Y value has to be $\sim$0.33 or both values should change by an intermediate amount.

The C/O ratio should increase with time because according to present ideas of GCE, O is produced by massive stars (MS), $M \gtrsim 10\ M_\odot$, while ^{12}C is mostly produced by intermediate mass stars (IMS), $1 \lesssim M/M_\odot \lesssim 8$ (e.g. Sarmiento and Peimbert 1985, and references therein). Therefore, a delay in the return of C relative to O, to the ISM is expected. Consequently the less evolved the object, the smaller the C/O ratio; this is what has been found in galactic and extragalactic H II regions (e.g. Dufour 1985; Pagel 1985; Peimbert 1985).

If it is assumed that most of the ^{12}C produced by IMS is due to objects in the $3 \lesssim M/M_\odot \lesssim 8$ range (that instant recycling applies) then it is possible to explain the ^{12}C/^{13}C ratio of the ISM but not the solar one (see Sarmiento and Peimbert 1985). To be able to explain the ^{12}C/^{13}C difference between the solar and the ISM values one would have to assume that part of the ^{12}C in the Sun is due to SN just prior to the formation of the solar system, which would raise the ^{12}C/^{13}C ratio because MS mainly produce ^{12}C, or that a substantial fraction of the ^{12}C produced by IMS is due to stars in the $1 \lesssim M/M_\odot \lesssim 2$ range and that the instant recycling approximation does not apply.

It seems that GCE cannot explain differences in the Ne/O and Ar/O ratios since O, Ne and Ar are ejected to the ISM by the same process: SN explosions of MS; moreover in galactic and extragalactic H II regions of different O/H ratios, the Ne/O ratio is constant within observational errors which is in agreement with the idea that the same process is responsible for the O and Ne enrichment of the ISM (e.g. Vigroux *et al.* 1985).

3.2 SN, MESF, Abundance Fluctuations

Cameron and Truran (1977) and Reeves (1978, see also Schramm and Olive 1983) suggested SN as the trigger for the formation of the solar system. The idea came from trying to explain the abundances of ^{26}Al and ^{107}Pd which have half lives of only about a million years. Clayton (1984) has argued that SN cannot account for the ^{26}Al present in the galaxy, and suggests novae instead. Peimbert and Sarmiento (1984) have found that the mass ejected per nova outburst is an order of magnitude smaller than previously thought, which complicates Clayton's proposal. Cameron (1985) has suggested that red giant stars through the ejection of PN are responsible for the ^{26}Al in the solar system, this proposal is based on several parameters that are uncertain at present. The outcome of this discussion is that it is not easy to explain the abundance of ^{26}Al in the solar system and that the evidence from radioactive elements in favor of a SN as the trigger of the formation of the solar system is not as compelling as it was a few years ago.

SN with $M \gtrsim 10\ M_\odot$ are expected to produce practically all the O in the ISM. Therefore, SN could be responsible for the factor of two enrichment in O/H of the material from which the Sun was formed.

SN models with $M > 10\ M_\odot$ do not produce appreciable amounts of freshly made helium, moreover according to stellar evolution models of IMS (e.g. Renzini and Voli 1981) and observations of planetary nebulae (e.g. Peimbert and Serrano 1980; Peimbert and Torres-Peimbert 1983) it is known that a good fraction of the freshly made helium is due to IMS (e.g. Serrano and Peimbert 1981). Therefore if the solar O/H enrichment is due to SN then a deficiency in the solar He/O ratio relative to the Orion nebula one would be predicted in agreement with observations.

The Crab nebula is not O rich, is overabundant in He and apparently originated from a star with $M \sim 8\ M_\odot$ (Davidson *et al.* 1982). Therefore SN like the Crab cannot explain the solar O/H excess nor the solar He/O defficiency. Consequently the SN considered in Table II are objects with masses larger than $10\ M_\odot$, according to models, or like Cas A, according to observations.

Since IMS produce most of the C abundance in the ISM, it means that if SN are responsible for a factor of 2 increase in the solar O/H they are responsible for less than a factor of 1.4 increase in ^{12}C and that they cannot explain all of the difference in the $^{12}C/^{13}C$ ratio. More specifically if 1/3 of ^{12}C is due to MS and 2/3 to IMS and since IMS produce all of the ^{13}C then for a factor of two increase in O/H we would expect a change in the $^{12}C/^{13}C$ ratio from 45 to 60 in the ISM and the difference between 60 and 90 would have to be attributed to GCE.

As mentioned before SN are not expected to change the O/Ne/Ar ratios.

To be able to explain the G dwarf problem and based on the idea that the higher the cooling in the ISM the easier it is to make stars Talbot (1974, see also Talbot and Arnett 1974, and Pagel and Patchett 1975) suggested that stars were formed with a metallicity higher than the average, the metal enhanced star formation model MESF. For ISM heavy element abundances of half the solar value the enhancement effect is of about a factor of two. This case might reduce to the SN one because the inhomogeneities in the ISM needed for the MESF model are most easily produced by SN explosions. Evidence for ISM abundance inhomogeneities, in addition to that derived from isolated SN remnants, comes from observations by Rosa and Mathis (1985) of 30 Doradus, which is an active star forming region, where they find a position with an overabundance in O/H of a factor of about five relative to other positions inside the H II region.

3.3. Accretion of Comets, Planetesimals, and Molecular Cloud Material

It is well known that conventional solar models are able to explain the solar neutrino experiment for very low values of Z and Y (e.g. Torres-Peimbert *et al.* 1969; Abraham and Iben 1971; Bahcall and Ulrich 1971); for solar interior Z values about an order of magnitude smaller than the photospheric one. To explain the solar neutrino experiment, Joss (1974) suggested that the Z value of the solar outer convective envelope might be higher than the interior one. To produce this difference, he proposed accretion of fractionated material in the form of planetesimals and comets, composed almost entirely of heavy elements, onto the solar surface after the end of the Hayashi convection phase. A lower Z value of the solar interior would reduce the thickness of the outer convection zone favoring this effect. Christensen-Dalsgaard *et al.* (1979) have made solar models with low Z values that turn out to have: thin convective envelopes, low neutrino fluxes and low Y values; nevertheless they point out that the solar oscillations predicted by their models seem to favor models rich in Z throughout.

The cometary material captured by the Sun is expected to be rich in O, less rich in C and poor in He, Ne and Ar compared to the solar values. Therefore, this effect would increase O/H, decrease He/O, C/O and (Ne, Ar)/O and probably would leave unaffected $^{12}C/^{13}C$.

Since the deficiency in (Ne,Ar)/O is less than a factor of two it could be argued that this effect has increased O/H in the outer convective zone by at most a factor of two. A factor of two would help in reducing the discrepancy between the observed and predicted solar neutrino flux but it is not enough to explain it.

Stellar accretion of molecular cloud material has also been considered in the literature (e.g. Yoshii 1981), nevertheless the similar $^{12}C/^{13}C$ ratio in the solar photosphere and in meteorites as well as the very different ISM value indicates that this process is not very important.

3.4 Solar Wind

Luck and Lambert (1985) have suggested that the solar wind might be responsible for the high O/H value in the solar photosphere. The solar wind is O/H poor which means that the O/H in the photosphere is increasing. A quantitative evaluation of this mechanism requires a knowledge of the mass loss rate and of the size of the convective envelope during the solar history.

It is not clear if the solar wind could explain changes in the C, Ne, Ar to O ratios, nevertheless, it is not expected to produce a change in the $^{12}C/^{13}C$ ratio since the photospheric and meteoritic values are very similar. If an increase in the O/H photospheric value is produced by this mechanism the He/O value is expected to remain constant or even to increase because the He/H deficiency in the solar wind is larger than the O/H deficiency (e.g. Meyer 1985b).

4. CONCLUSIONS

The O/H ratio is higher in the photosphere of the Sun than in the Orion nebula. There are at least three possible explanations for this difference: a) an O/H enhancement over the average value of the ISM due to SN, b) accretion of planetesimals and cometary material expected to be rich in O/H, and c) solar wind observed to be poor in O/H.

If an O/H fluctuation in the ISM due to SN is responsible for the high solar O/H value then differences in the He/O, C/O and $^{12}C/^{13}C$ ratios would also be expected but not in the (Ne, Ar)/O ratio.

An O/H increase of a factor of two in the Sun due to SN implies an enhancement of ^{12}C of about 4/3 and an increase in $^{12}C/^{13}C$ from 45 to 60. Therefore, GCE is needed to explain the rest of the change in the $^{12}C/^{13}$ ratio.

The change in the $^{12}C/^{13}C$ ratio between the Sun and the ISM implies that the instant recycling approximation does not apply and that a good fraction of ^{12}C is due to stars in the 1-2 $M_{\odot}$ range.

If accretion is responsible for the O/H difference, then also differences in He/O, C/O and (Ne, Ar)/O would be expected. Since the (Ne, Ar)/O deficiency is less than a factor of two, the accretion mechamism is not very effective and the Z content of the Sun cannot be smaller than 1/2 of the photospheric value. This lower Z value is not low enough to explain the solar neutrino experiment but goes in the right direction.

If the solar wind is responsible for the O/H increase, then the Y value in the photosphere of the Sun would have to be higher than ∿ 0.40 (neglecting helium gravitational settling).

Better He/H, Ne/O and Ar/O determinations for the solar system are needed to advance in this subject.

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KUTNER: The current view of the molecular results corrected for radiative transfer and fractionation indicates a $^{12}C/^{13}C$ ratio close to the terrestial value, with no evidence for variation with R.

PEIMBERT: For the ISM near the sun I am using the $^{12}C/^{13}C$ results derived from CH^+ observations in the visual region. I consider them to be more accurate than the values derived from observations in the radio region.

WILSON: I do not believe that the $^{12}C/^{13}C$ ratio is a constant in the galactic disk. However, *near the sun*, the radio data give a value of about 70. The isotope ratio from CH^+ toward ρ Oph disagrees strongly from this value. Closer to the galactic center, the $^{12}C/^{13}C$ ratio appears to be lower. D. Lambert comments that the element abundances in O-star atmospheres differ from the Orion nebula values.

STARK: I also disagree with the comment by Marc Kutner. Much of the work on ^{13}C to ^{12}C ratios in millimeter lines of CO has been done at AT & T Bell Laboratories, and in a recent review of our work, Arno Penzias argued that all our data indicated a ^{12}C to ^{13}C ratio of about 60 in the solar neighborhood, and a lower value, about 25, in the galactic center region.