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TEMPERATURE FLUCTUATIONS IN NEBULAE

John S. Mathis
Dept. of Astronomy, Univ. of Wisconsin, 475 N. Charter St., Madison WI 53706-1582, USA

RESUMEN

Hay un serio problema en nuestra comprensión de regiones H II y nebulosas planetarias que debe resolverse antes de que podamos sentirnos seguros de la determinación de abundancias en nebulosas. Por una parte, hay fuertes indicaciones de que existen fluctuaciones de temperatura en la nebulosa mucho mayores de lo que los modelos predicen. En este caso las abundancias derivadas de las líneas prohibidas de excitación colisional, usando la temperatura media del [O III], están subestimadas por factores de 2 o más. En las regiones H II cercanas y bien observadas, estas abundancias tienen aproximadamente la mitad del valor solar. En contraste, las líneas de recombinación de los mismos iones sugieren abundancias solares. En este artículo se mencionan algunas de las posibles causas de estas fluctuaciones y se incluye una nueva sugerencia relacionada con la interfaz conductiva entre material del viento estelar chocado y la nebulosa visible de 8 000 K. Este mecanismo no es muy satisfactorio para proveer las fluctuaciones observadas. Hay también buenas razones para creer que las abundancias en nebulosas tienen aproximadamente la mitad del valor solar. El mejor argumento es que las estrellas B, recién formadas en el medio interestelar, tienen valores de (C,N,O)/H de la mitad de los valores solares. Además, las abundancias de los elementos en la fase gaseosa del medio interestelar, más el O o N en granos, no son mayores que un medio de las abundancias solares. Las líneas de recombinación en radio también indican que el promedio de la temperatura en la Nebulosa de Orión es aproximadamente la del [O III].

ABSTRACT

There is a major problem in our understanding of H II regions and planetary nebulae (PNe) that must be resolved before we can feel confident about abundance determinations in nebulae. On one hand, there are strong indications that there are large fluctuations of the nebular temperature, far in excess of what photoionization models predict. In this case abundances derived from collisionally excited forbidden lines, using the mean [O III] temperature, are underestimated by about a factor of two or more. Such abundances are about half solar for nearby well-observed H II regions. In contrast, the recombination lines from the same ions suggest about solar abundances. This paper mentions some possible causes for the fluctuations, including one new suggestion involving the conductive interface between hot shocked stellar wind material and the visible 8 000 K nebula. This mechanism is not very promising for providing the observed T-fluctuations. There are also good reasons to believe that abundances in nebulae really are about half solar. The most powerful argument is that B stars just formed from the ISM have about half the solar (C,N,O)/H. Also the gas phase abundances of elements in the interstellar medium, plus the O or N in grains, cannot account for more than about half of the solar abundances. Radio recombination lines also indicate that the average temperature in the Orion Nebula is about that from [O III].

Key words: **ISM: ABUNDANCES — H II REGIONS — PLANETARY NEBULAE**

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1. INTRODUCTION

The chemical compositions of ionized nebulae, either H II regions or planetary nebulae (PNe), are usually determined in a straightforward, simple way. Unfortunately, the results may be subject to systematic errors of almost a factor of two, as has been emphasized for many years by M. Peimbert and his colleagues (see especially the Peimbert 1995 review).

Suppose we want to determine the abundance of the ion X relative to H^+ in a bright nebula. We estimate a mean nebular temperature by means of collisionally excited lines, usually [O III] λ4363/5007, and then assume that this T([O III]) is appropriate for determining all line emissivities, $j_\lambda(\mathrm{X},T)$. Then abundances follow from $n(\mathrm{X})/n(\mathrm{H}^+) = [I_\lambda(\mathrm{X})/j_\lambda(\mathrm{X})][j(\mathrm{H}\beta)/I(\mathrm{H}\beta)]$, using T([O III]) when evaluating the j's.

This procedure is being challenged by increasingly accurate observations of recombination lines of both O II and C II, both involving permitted transitions. These lines are quite faint ($\lesssim 0.002\, I(\mathrm{H}\beta)$), but modern detectors can measure them accurately. It is legitimate to question whether the faint recombination line strengths can be accurately compared directly with Hβ, a thousand times stronger; there are prior incidents of inaccurate strengths of faint lines. For the present types of observations, though, the data seem valid.

Both the collisionally excited [O III] lines and the O II recombination lines arise from encounters of O^{+2} with electrons and so should be produced in similar parcels of plasma. However, the cross sections of the collisional interactions increase with energy (or, equivalently, T_e), while recombinations decrease. If T([O III]) is used to compute the λ5007 emissivity relative to Hβ, the derived $n(\mathrm{O})/n(\mathrm{H})$ value is roughly half solar for all of the well-studied H II regions (the Orion Nebula, M 8, and M 17; Peimbert, Torres-Peimbert, & Ruiz 1992; Peimbert, Storey, & Torres-Peimbert 1993; Peimbert, Torres-Peimbert, & Dufour 1993). If the same T([O III]) is used with the O II recombination lines, the abundances more than double. Exactly the same type of discrepancy is found for C^{+2}; the $n(\mathrm{C}^{+2})/n(\mathrm{H}^+)$ ratio from the recombination line λ4267 is larger than from the collisionally excited C III] λ1907, 1909 by up to an order of magnitude.

A similar effect is observed for the H recombination processes. The relative strengths of the Balmer lines reflect the reddening of the nebula by dust (being almost independent of T or n_e), but there is a significant difference in the T-dependence of the emissivities of the Balmer continuum ($\propto T^{-1.5}$) and Hβ ($\propto T^{-0.89}$). The temperature derived from $I(\mathrm{Bac})/I(\mathrm{H}\beta)$ is systematically lower than T([O III]) in H II regions and PNe. Liu & Danziger (1993) have found mean values for 30 well-determined PNe of T(Bac) =10 600 K and T([O III]) = 12 000 K.

A solution of these discrepancies, initially suggested by Peimbert (1967), is to have large fluctuations of temperature within the nebulae, so that the comparatively hot plasma producing the collisionally excited lines is *not* the same as the material producing the recombination lines. In this paper I will review some possible causes of such T-fluctuations, including an attempt to explain them by a recently-calculated mechanism, and then discuss some problems with the idea that large T-fluctuations exist in most H II regions and PNe.

2. DESCRIPTIONS OF TEMPERATURE FLUCTUATIONS

In each nebula we observe intensities that are the emissivities of the various lines or continua integrated along the entire path length s through the nebula. For a line arising from the ion X we have

$$I(\lambda) = \int j_\lambda n_e\, n(X)\, ds\,, \tag{1}$$

where $j(\lambda)$, the ionic emissivity (erg cm^3 s^{-1} sr^{-1}), is a strongly increasing function of T for collisionally excited lines and depends inversely on T for recombination lines and atomic continua.

2.1. Peimbert's Formalism

Peimbert (1967) expanded the integrand in (1) in a Taylor series about a mean temperature T_0, using the definition of T_0 to eliminate the first-order term, and stopped at the second-order term, to obtain

$$I(\lambda) = \int \bar{j}_\lambda n_e\, n(X)\, ds\,; \tag{2}$$

$$\bar{j} = j_\lambda(T_0)\,[1 + j''(T_0)t^2/2]\,; \tag{3}$$

$$T_0 \equiv \frac{\int T n_e\, n(X)\, ds}{\int n_e\, n(X)\, ds}\,, \tag{4}$$

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where primes are derivatives with respect to T, easily computed, and t^2 is a parameter representing fluctuations of the actual T about the mean:

$$t^2 \equiv \int (T-T_0)^2 n_e\, n(X)\, ds \Big/ \left[T_0^2 \int n_e\, n(X)\, ds\right] . \tag{5}$$

If the emissivities are

$$\begin{aligned} j(T_0) &\propto T_0^{-\alpha_1} && \text{(recombination line)} ;\\ &\propto T_0^{-\alpha_2} \exp(-\Delta E/kT_0) && \text{(collisional line)} ;\\ &\propto T_0^{-\alpha_3} && \text{(continuum)} , \end{aligned}$$

where the α's are constants, then $j''(T_0)$ is given by

$$\begin{aligned} T_0^2\, j''(T_0) &= j(T_0)\, \alpha_1(\alpha_1+1)/2 && \text{(recombination line)} ;\\ &= j(T_0) \left[(\Delta E/kT_0)^2 - 2(\alpha_2+1)(\Delta E/kT_0) + \alpha_2(\alpha_2+1)\right] && \text{(collisional line)} ;\\ &= j(T_0)\, \alpha_3(\alpha_3+1)/2 . && \text{(continuum)} . \end{aligned}$$

The fluctuation parameter t^2 and mean temperature T_0 are estimated by using two T-sensitive ratios, perhaps expressed as T(Bac) and T([O III]), and solving for t^2 and T_0 using the expressions above. One can also find the two parameters by requiring the same abundance (X/H^+) from recombination lines and collisionally excited lines of the same ion, such as C^{+2} or O^{+2}. Common values for t^2 are in the range 0.03 – 0.05 for H II regions and 0.03 – 0.09 for PNe.

These values of t^2 are really quite large, with an rms fluctuation, $(t^2)^{1/2}$, ≈ 0.2. Models of PNe and H II regions do show a variation of T with radial distance r from the exciting star, caused by the hardening of the average photon energy with r because of the ν^{-3} dependence of the absorption cross sections of H and He. However these variations correspond to $t^2 \leq 0.01$. Even worse, my models of a dense H II region (resembling the Orion Nebula) show the ***wrong sign*** in the difference of the T([O III]) and T(Bac)! Over the rather wide range of $400 \leq 10^6$ O/H ≤ 1000, $T(\mathrm{Bac}) \approx 1.04\, T$([O III]). The hardening of the photons causes T to rise in the outer layers of the model, where oxygen is mostly singly ionized. Hence much of the Balmer continuum and Hβ come from the warmer regions that are not contributing to [O III], and the weighting of the H radiation towards low T is more than offset by the fact that the average H^+ being warmer than the average O^{+2}.

2.2. An Alternative Formalism

Peimbert's scheme is, of course, not unique. If we had some prescription for a physical mechanism for the fluctuations, we would write, in place of (1),

$$I(\lambda) = \int j_\lambda(T)(d\tau/dT)\, dT , \tag{6}$$

$$d\tau \equiv n_e\, n(X)\, ds , \tag{7}$$

where the physical prescription would provide the function $d\tau/dT$, which is the distribution of the emission among the various temperatures. The usual Peimbert scheme assumes that $j_\lambda(T)$ can be replaced by the emissivity at a single temperature that is the average, T_0, corrected by a $j''_\lambda(T_0)$ term because of the particular T-dependence of the emissivity.

In order to test how differing amounts of plasma of two temperatures affect the derived abundances, I postulate a simple expression for $d\tau/dT$:

$$d\tau/dT = C\, \delta(T-T_1) + (1-C)\, \delta(T-T_2) , \tag{8}$$

where δ is the Dirac delta-function. In other words, I assume that a fraction C of the emission arises from temperature T_1 and the rest from T_2; an extreme picture of T-fluctuations, but serving to suggest what

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TABLE 1
RESULTS OF A TWO-T MODEL FOR AN H II REGION[a]

$T_{\rm Bac}$	T_1	C^b	T_2	$\epsilon_{\rm O}$([O III])[c]	$t^2_{\rm P}$	$\epsilon_{\rm O}$(P)[d]
8600	8600	All	8600	0	0	0
7403	10000	0.222	7000	0.354	0.026	0.058
7091	13000	0.043	7000	0.494	0.032	0.178
7051	9000	0.518	6000	0.380	0.033	-0.017
6724	9250	0.357	6000	0.495	0.040	0.945
6095	12000	0.050	6000	0.722	0.054	0.394

[a] All models have T([O III]) = 8600 K.
[b] C = fraction of $\int n_e n(X) ds$ at temperature T_1; $(1 - C)$ at T_2.
[c] $\epsilon_{\rm O} \equiv$ error in $({\rm O}^{+2}/{\rm H}^+)$ = (1 – calculated/true). The error when T([O III]) is used in all emissivities (the "standard" approach).
[d] $t^2_{\rm P}$ and $\epsilon_{\rm O}$ are the fluctuation parameter and error for the Peimbert formalism.

parameters are important and to determine how well the Peimbert formalism can predict the correct abundances in a situation for which it is not ideally tailored. The various emissivities follow from (6) and (8). I vary T_1 and T_2 rather arbitrarily, but with the restraint that the resulting T([O III]) = 8 600 K, a reasonable value for the center of the Orion Nebula. For a given C and T_2, T_1 is adjusted until T([O III]) = 8 600 K, and T(Bac) follows. The $n({\rm O}^{+2})/n({\rm H}^+)$ predicted from [O III] λ5007 and Hβ is then compared to the $n({\rm O}^{+2})/n({\rm H}^+)$ in the model. The T(Bac) and T([O III]) also provide the $n({\rm O}^{+2})/n({\rm H}^+)$ from the Peimbert formalism.

The results are summarized in Table 1, in which the $\rm O^{+2}$ abundances derived using T([O III]) in the emissivities, relative to the $\rm O^{+2}$ in the model, are given for some values of T(Bac).

We see that the use of T([O III]) alone leads to serious errors in $n({\rm O}^{+2})/n({\rm H}^+)$ even if a modest amount (22%) of 10 000 K gas is present along with 7 000 K gas. Not surprisingly, if one knows the T(Bac) and can perform Peimbert's correction scheme, the error in abundance is reduced considerably. The negative value of the Peimbert error shows the Peimbert scheme can give an estimate that is slightly too high. A comparison of the third and fourth entries in the table shows that a small amount of hot gas has more effect than a large amount of cool gas, so that it will perhaps be difficult to explain the observations by having cool spots producing the recombination lines while most of the gas is close to the [O III] temperature. The penultimate line shows that a factor-of-two error in the "standard" abundance estimate occurs at about t^2(Peimbert) $\approx$ 0.04. The last entry shows that at large t^2 the Peimbert scheme underestimates the O abundance, but does much better than simply using T([O III]) alone.

It is clear that some form of estimate of T besides collisional lines is very helpful. I suspect that the Paschen discontinuity relative to Hα is better than the Balmer jump relative to Hβ. The T dependences of the emissivities are the same and the reddening correction is much less. Perhaps the weakness of the Paschen continuum relative to the starlight (which should have practically no Paschen discontinuity in it) makes the method less reliable.

3. PHYSICAL MECHANISMS FOR PRODUCING T-FLUCTUATIONS

We now consider various ways that such T-fluctuations can come about (see Peimbert 1995 for a discussion of some others that seem less than promising):

1. Perhaps the best explanation, partly because it is very difficult to quantify, is that there are local regions heated by shocks or dissipation of the turbulent (non-thermal) motions that are observed to exist in nebulae. The shocks might arise from the interaction of the stellar wind with the nebula. Falgarone & Puget (1995) have given an interesting discussion of intermediate turbulence, based on laboratory data, in which they suggest that dissipation might be local and lead to strong local heating. Elmegreen (1995) has strongly emphasized the importance of turbulence within the ISM, and T-fluctuations may be yet another manifestation.

2. If grains can be moved through the surrounding gas, it is possible to imagine that there might be clumps of grains that produce strong variations in the local cooling and, therefore, the temperature. I feel that this is a remote possibility because (a) grains are highly charged in a plasma, making it difficult to move them through

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the gas because of the Coulomb interactions; (b) grains are observed not to contain most of the best coolant, oxygen, in the diffuse ISM; (c) a very large variation in the O/H ratio is required to produce the required range of temperatures.

3. Nebulae are very clumpy, so the usual models, filled with uniform gas, all of which is illuminated by the exciting star, are not very realistic. This fact is often taken into account by modelers by interpreting line-of-sight intensities by volume averages of their models. In real objects shadows of the internal nebular blobs must be common. The temperature within the shadows, where the mean photon energy is much less than in the directly illuminated portions of the nebula, must be appreciably less than in the usual models, while the directly illuminated portions are warmer than they would be without neighboring shadowed regions. If the ionizing radiation is suddenly withdrawn from a plasma, the gas cools faster than it recombines. Hence these shadows may produce cool regions without recombination.

4. It is well known that the material that is optically visible in H II regions and PNe occupies only a small fraction (typically $< 10\%$) of the volume of the objects, based on the comparison of the nebular densities as measured from forbidden line diagnostics with the it rms density from the de-reddened Hβ and other H lines. This small filling factor is, presumably, caused by confinement of the visible material by the pressure of hot, tenuous gas, perhaps arising from the stellar wind colliding with the surrounding nebular material. Heat must flow from the hot gas to the visible.

Maciejewski, Mathis, & Edgar (1995) have calculated the effects of the conductive interface on the production of λ4363 and other lines. In this model, all lines except λ4363 are produced in the photoionized region as in usual H II region models, but λ4363 arises both from the H II region and from a region in the conductive interface with $T \approx 30\,000$ K. At higher T the oxygen is collisionally ionized beyond O^{+2}. However, the production of λ4363 is rather modest; for conditions approximately like the Orion Nebula, ≈ 200 interfaces (!), if each is viewed normally to its surface, are needed to produce enough λ4363 to make an error of a factor of two in the O/H ratio. A magnetic field could further suppress the effect of the conductive interface. Of course one expects about a factor of two increase in the production of λ4363 from viewing the interfaces at angles other than the normal, and each free-standing sheet of visible material would have 2 interfaces, but still this idea requires ≈ 50 free-standing sheets of visible material. I feel that it does not seem very attractive, but maybe it is not impossible. The *Hubble Space Telescope* (*HST*) pictures of the Orion Nebula show extremely fine-scaled structure down to the limit of resolution, 0.05 $''$ (O'Dell, Wen, & Hu 1993). If there are as many as 50 sheets, one might not expect to find large fluctuations in surface brightness because of large-number statistics. We will tentatively discard this explanation, but keep it in mind.

4. EVIDENCE *AGAINST* LARGE T-FLUCTUATIONS

In spite of the strong evidence for large T-fluctuations provided by the strengths of recombination lines, including O, C, and He, there is also good evidence that somehow those lines are selectively produced in peculiar regions, and that the chemical composition of H II regions and PNe is well given by emissivities using T([O III]).

4.1. Depletions in the ISM

Gas-phase ionic abundances are obtained in the ISM by means of absorption lines (mostly in the satellite ultraviolet) seen against the spectra of suitable background stars (see a review in Jenkins 1987). The ISM lines are distinguished from the stellar photospheric absorption by their narrow widths, and hot stars (types O, early B) with relatively simple photospheric spectra are used whenever possible.

Usually it is assumed that the total abundances of elements in the ISM should be solar, and the difference in the gas-phase abundance and the solar is attributed to some of the elements being in grains. With this assumption, almost all of certain elements (Fe, Mg, Si, Al, and others) are in the grains, while most of others (especially Zn and S) is in the gas.

Recent accurate studies of depletions using the Goddard High Resolution Spectrograph of the *HST* (Sofia, Cardelli, & Savage 1994), as well as *Copernicus* observations, have interesting implications for the compositions of grains, and show that there is a *major* problem arising from assuming that the true abundance in the ISM is solar. The *gas phase* abundances, expressed per 10^6 H atoms, are typically (O/H) ≈ 300, (N/H) ≈ 70, and (C/H) ≈ 150. The problem is, "Where is the missing O, if the ISM has solar abundances?" Of course, some O can be included in grains, as silicates and/or oxides. For each 10^6 H atoms there are about 38 of Mg, 47 of Fe, 35 of Si, and 16 of S (Anders & Grevasse 1989). Of the remaining, excepting noble gases and CNO, only four (Na, Al, Ca, & Ni) are > 1. Each Mg, Fe, and Si can combine with $1 - 2$ O's, so perhaps as many as 180

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TABLE 1

O/H IN VARIOUS OBJECTS

Object	10^6 O/H	Reference
Sun	740 ± 90	Grevasse & Noels (1993)
	851 ± 71	Anders & Grevasse (1989)
ISM, gas-phase	300 ± 50	See text
ISM, oxides	180 ± 50	See text
ISM, water ice	< 4	VI Cyg No. 12; see text
Total ISM	480 ± 70	Sum of lines above
B stars: Orion Assoc.	505 ± 37	Cunha & Lambert (1994), NLTE
B stars: Trapezium	708 ± 78	Cunha & Lambert (1994), NLTE
B stars: field	480 ± 180	Gies & Lambert (1992)
B stars: Ori OB 1	364 ± 44	Kilian (1992)
B stars: nearby cluster	407 ± 50	Kilian, Montenbruck, & Nissen (1992)
B stars: Field	295 ±48	Kilian (1992)

O's can be combined into the grains, to total 480 for the dust plus the gas. The solar abundance of O/H is not as well determined as the quoted errors would suggest (see Table 2 below); the lower value is 740 $\times 10^{-6}$, and there seems to be no obvious way to account for the "missing" 260 $\times 10^{-6}$.

The obvious partners for combining with the interstellar O are C or H. However, water has a strong O–H stretch band at 3.07 μm that is *not* seen, to considerable accuracy, in the diffuse ISM (but, of course, *is* seen deeper within molecular clouds.) The absorption cross section of the band is well known (see a discussion in Whittet 1992). For the heavily reddened star VI Cyg No. 12 (Pendleton et al. 1994), I estimate that the upper limit on the ice band corresponds to O/H $\leq 4 \times 10^{-6}$, utterly negligible in accounting for the O. A very similar remark holds for nitrogen, which has a band at 3.0 μm that is not seen.

Can O hide in the molecule CO? Certainly not. On the theoretical side, there is a major problem in getting enough C in the ISM to supply the C needed for the polycyclic aromatic hydrocarbon molecules and the λ2175 "bump", almost surely produced by carbon of some sort (see Mathis 1990 for a discussion). Observationally, CO is seen to be dissociated in the harsh radiation environments of the diffuse ISM. Its abundance in the diffuse ISM was observed by the *Copernicus* satellite to be $\ll 10^{-6}$ for most lines of sight (Federman et al. 1980). The most molecule-rich line of sight in the *Copernicus* survey, ζ Oph, has a good determination of CO (Lambert & Federman 1995), and $CO/(H + 2H_2) = 1.5\ 10^{-6}$. CO cannot be the means of hiding the O.

A very similar situation holds for N/H. The mean gas phase abundance in the diffuse ISM is $\approx 65 \times 10^{-6}$, while the solar is 110 $\times 10^{-6}$. There is no good way to condense out N into solids on grains except perhaps by means of a surface coating of ammonia. However, NH_3 has a strong absorption at 2.96 μm that is not observed.

4.2. Abundances in Young Stars

Both interstellar N and O are well accounted for if the true interstellar abundances are like the B stars that just formed from the ISM. Table 2 summarizes the (O/H) observations for the ISM and for B stars. Thus, we see fairly direct evidence that the composition of the nearby ISM is roughly half solar from the B stars that have recently formed from it, in agreement with H II regions, *assuming no T-fluctuations.* However, the abundances in the three Trapezium B stars (Cunha & Lambert 1994) are consistent with solar, and are appreciably larger than the other B stars. Has the entire Orion Nebula been enriched in O locally? One star (HD 37481) has (O/H) = (912 ± 185) 10^{-6}, more than solar, but within its same grouping there are stars of less than average (O/H). Perhaps local supernovae have created inhomogeneities within the cloud, along with somewhat of a gradient in (O/H).

The Si/H in the Orion stars (Cunha & Lambert 1994) is below solar: (14.7 ± 1.12) 10^{-6}, compared with 35 in the Sun. The Trapezium stars, seen as somewhat O rich, are average for the other Orion B stars in Si/H: (15.9 ± 1.1) 10^{-6}, while solar is (35 ± 4). The mean C/H for the non-Trapezium stars is (246 ± 46) 10^{-6}. The only Trapezium star for which C/H is measured has (178 ± 26), while the solar is (363 ± 35). The failure of the Trapezium stars to seem enriched in Si and C, especially when Si/O would seem to be difficult to change

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by any processes within the B star itself, suggests to me that the enrichment of O/H in the Trapezium, relative to the other Orion B stars, should be treated with caution.

Note that if dust survives within the ionized portion of the Orion Nebula, with up to 180 O per 10^6 H in addition to the nebular oxygen, the nebular plus dust abundance would be on the high side of the B star photospheric abundances. However the nebular (gas phase) Fe/O seems approximately solar, so the Fe is probably not mainly in the grains.

B stars contain (N/H) $\approx 65 \times 10^{-6}$, somewhat smaller ($\approx$ 0.2 dex) than the typical N/H in the gas phase in the diffuse ISM, so using B stars as the true ISM abundances would nicely explain the "missing" N/H.

4.3. Radio Measurements of Nebular Temperatures: Final Remarks

Near the center of the Orion Nebula the electron temperature is observed to be $\approx$ 8 500 K, as determined from the recombination lines H 110α and H 137β to be 8500 K (Wilson & Jäger 1987) near the peak emission to which many optical observations refer. Since the central T([O III]) is equal to the radio temperature, this measurement suggests that there is no discrepancy between recombination and collisional temperatures. Walter & Dufour (1994) have found that T(Bac) = 8400 K near the Trapezium in the Orion Nebula, in excellent agreement with T([O III]) and the radio recombination lines.

The dispersion of O/H and other elements within clusters is very interesting: if one takes the errors seriously, there seems to be an intrinsic spread in abundances within the same association, such as the groupings within Orion studied by Cunha & Lambert (1994). I wonder if such inhomogeneities might arise deep within the molecular cloud soon after star begins.

The larger ultraviolet extinction in the diffuse ISM, with $R \approx 3.1$, as compared with the outer parts of dense clouds, with $R > 4$, shows that small grains coagulate into larger ones within clouds. Large grains are colder than small, and deep within clouds there is very little radiation for heating the grains. I wonder if *all* elements within the ISM are not almost completely frozen onto grains within the cores of the clouds (the microwave molecular emissions represent a trivial fraction of the major elements), and then grains are segregated within the cloud by radiation pressure, after a star begins to form, or some sort of wave motions to which they respond differently from the gas. Then pockets of gas rich in heavy elements, and also ones somewhat depleted, would form and produce the dispersion in abundances seen among the stars in a given grouping. In this way the Sun could have formed and be richer in heavy elements than the average of the ISM today.

We are left with an unsatisfactory but very interesting conclusion: that there may be large systematic errors in abundance determinations in nebulae, if based upon T([O III]) alone, but we cannot be sure at the present time. I suspect that the truth lies in the middle of the range between the current value of the solar (O/H), 740×10^{-6}, and the nebular values of (O/H) based upon T([O III]). I can only emphasize the warnings that such systematic errors *might* exist, and to try to have everyone interested in abundances aware that present-day published determinations are deeply suspect.

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