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# Light elements as probes of weak stellar winds

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**Abstract.** The possibility that stars of the upper main sequence possess weak winds (of order $10^{-14}$ to $10^{-12}$ M$_\odot$ yr$^{-1}$) that may compete with atomic diffusion has been suggested by several authors, particularly by Babel & Michaud (1991a) and Babel (1992). Such winds may affect the chemical abundances that appear in the atmospheres of these stars. However, obtaining unambiguous evidence for the existence of a weak wind is not easy. We consider the possibility that naturally abundant chemical elements such as C, O and Ne, which are *not* expected to be made overabundant in a stellar atmosphere by radiative levitation, may accumulate in or near the photosphere of a mass-losing star, thus serving as tracers of mass loss.

We first show that the most abundant elements are not expected to be overabundant in the atmospheres of main sequence stars in the range $8\,000 \leq T_{\rm e} \leq 15\,000$ K due to radiative acceleration. We next show that hydrogen mass loss from the atmosphere, at a rate in the range of roughly $10^{-14} \leq \dot{M} \leq 10^{-12}$ M$_\odot$ yr$^{-1}$, could lead to accumulation of a few abundant elements in or not far below the stellar photosphere, provided that any turbulence in the wind at the level of the photosphere is not sufficient to prevent diffusion. We find that such mass loss in late B stars should lead to observable overabundance of Ne, while in early A stars, such mass loss causes O to accumulate in the atmosphere. Detection of overabundances of these elements would provide direct evidence of the presence of weak mass loss. The few available Ne abundance determinations do not allow us to decide whether such weak winds are present in any B stars, but numerous measurements of O abundance imply that either winds in this mass loss range do not occur, or else that atmospheric diffusion is prevented by turbulence in early A stars.

**Key words:** stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: mass loss

## 1. Introduction

One of the most striking contrasts between the atmospheres of upper and lower main sequence stars is found in the different behaviour of relative chemical abundances. In lower main sequence stars, which span a large range of ages, most of the observed abundance differences at a given effective temperature are due to secular variation in the chemical abundance mix of the interstellar medium from which the stars formed, leading to observed abundances that depend essentially on the inferred age of a star. At a given age (as measured by the ratio [Fe/H] for example), there is hardly more dispersion in the relative abundances of easily measured elements than may be attributed to observational error (Abia et al 1988; Andersen et al 1988; Nissen & Edvardsson 1992). (The light element Li, which is greatly affected by nuclear reactions in the deep envelope of the star, is an exception to this general behaviour.) In contrast, the upper main sequence stars, all of which are sufficiently young (ages $\leq 10^9$ yr) that secular variations of galactic chemical abundances have almost no influence, show completely different behaviour. Among such stars, very large variations in abundance patterns have led to the identification of a variety of peculiarity classes, including metallic line (Am) stars, $\lambda$ Boo stars, SrCrEu and Si peculiar A (Ap) stars, HgMn Ap stars, and He-weak and He-strong B stars. At least $\sim 10\%$ of upper main sequence stars between spectral classes F0 and B2 are sufficiently peculiar even in low dispersion spectra to be classified as members of one of the peculiar classes. In some peculiar upper main sequence stars, the chemical abundance anomalies occur in the form of underabundances of certain elements (metals in $\lambda$ Boo stars, Ca and Sc in Am stars, or He in He-weak stars), but more commonly the obvious anomalies are (sometimes dramatic) overabundances of certain species, such as iron peak elements in Am stars, Ti, Cr and rare earths in SrCrEu Ap stars, Si in Si Ap and He-weak stars, Mn in HgMn Ap stars, and He in He-strong stars (see Dworetsky, Castelli & Farragiana 1993).

The variety of abundance patterns is indicative of the variety of physical effects occuring in the envelopes of main sequence stars that transport matter from one level to another. In stars without significant mixing or wind, there is a mutual diffusion of all the elements due to the effects of the pressure and thermal gradients, radiative accelerations, and concentration gradients, which has to be taken into account in computations of stellar models (Richard et al 1996). Opposing this separation of the chemical species are the vigourous mixing produced in

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the convection zones and, for example, the instabilities due to rotation-induced mixing (Zahn 1992).

In an atmosphere which is not losing mass to space, the major process known to be able to increase abundances of trace elements in the stellar atmosphere is levitation by selective radiative acceleration driven through spectral lines or continua. If below the atmosphere a force upwards, in excess of the gravitational force, is exerted by the radiation field on particular atomic species, and if this force diminishes in or above the atmosphere, an accumulation of the supported species in the atmosphere will occur. The concentration will eventually be limited by the contrary effects of concentration-driven diffusion, by rotationally-induced turbulence, by saturation of the lines supporting the atomic species as its abundance increases, or by instabilities. Calculations have shown that radiative acceleration is capable of supporting abundances that are substantially higher than the solar abundances for elements that are relatively low in natural abundance (see for example Vauclair 1983; also Michaud et al 1976, Alecian & Vauclair 1981, Borsenberger et al 1984, and Babel & Michaud 1991a).

A second process which may be able to lead to modest atmospheric overabundances is levitation by ambipolar diffusion of hydrogen (Babel & Michaud 1991b). This process is probably only effective in magnetic Ap stars with $8500 \leq T_{\rm e} \leq 12000\,{\rm K}$. In such stars, the zone of partial H ionization (normally mixed by convection) is stabilized by the strong magnetic field, and upward diffusion of protons (balanced by downward diffusion of neutral H) can lift trace atoms up through the partial ionization zone into the atmosphere. This process, which functions over only two or three scale heights, and only in regions of more or less vertical local magnetic field, cannot lead to large overabundances. However, it *can* support even abundant elements, as the levitation is not limited by spectral line saturation. This process will be discussed further in Sect. 5.

For radiative levitation, there exists a general maximum abundance that can be lifted into the atmosphere of a star, due to the saturation of the spectral lines through which radiation supports the element. It has been shown by Michaud et al (1976; hereafter MCVV) that this maximum abundance does not depend very strongly on atomic number, except that it is lowered somewhat for atoms which have noble gas or actinide-like atomic structure. However, the maximum abundance which can be supported by radiation does depend strongly on the effective temperature of the star. An order of magnitude estimate for the maximum abundance which can be supported is easily obtained from the results of MCVV. Their Eqs. (30) and (31) give an estimate of the radiative acceleration $g_{\rm R}$ to which an atom or ion $I$ is subjected as a function of its mass fraction $X_{\rm I}$, its atomic weight $A$, the local temperature $T$, and the available radiative flux (i.e. the effective temperature $T_{\rm e}$ of the star). Suppose that the element of interest is sufficiently abundant that its resonance spectral lines are saturated, and consider a point just below the atmosphere, where $T = 1.5\,T_{\rm e}$, and assume that the atom is not in a rare gas or actinide-like atomic configuration, and has resonance lines longward of the Lyman limit. Then we may invert their Eq. (30) to obtain the maximum mass fraction $X(Z)$ of the element of atomic number $Z$ that can be supported. Taking (conservatively) MCVV's high estimates for the parameters of the saturated forces (their Table 3), and requiring that the radiative acceleration $g_{\rm R} = 1\,10^4\,{\rm cm\,s^{-1}}$, we find that the largest mass fraction of an ion that may be supported is

$$X_{max}(Z) \simeq 8.6\,10^{-4} T_{\rm e4}^{7.0}/A^{0.8} \quad (1)$$

where $T_{\rm e4}$ is in units of $10^4$ K. The maximum supportable mass fraction will be substantially lower if the ion of interest has a noble gas or actinide electronic configuration. For a typical light element with $A \sim 16$ this expression indicates that at $T_{\rm e} = 8000\,{\rm K}$, the mass fraction $X(Z)$ that may be supported by radiation pressure for any particular element should not be larger than $2\,10^{-5}$, while at $T_{\rm e} = 15000\,{\rm K}$, not more than $2\,10^{-3}$ can be supported. At $T_{\rm e} = 20000\,{\rm K}$, this estimate indicates that a mass fraction as large as $1\,10^{-2}$ could be supported; for the light element He, the maximum supportable mass fraction might be as large as $4\,10^{-2}$. Note that this is not a large enough mass fraction to lead to a radiatively supported overabundance of He even at 20000 K, a result that has been confirmed by the detailed calculations of Michaud et al (1979).

Thus, among B and A stars, we expect radiative levitation to have the greatest effect on the atmospheric abundances of the normally unabundant elements. The naturally abundant trace elements C, N, O, Ne, and Fe, with mass fractions at solar abundance of $10^{-3}$ or more, are not expected to be made substantially overabundant by radiative levitation in the atmosphere of a star with an effective temperature below about 15000 K. Helium should not show a radiatively supported overabundance for $T_{\rm e} \leq 20000\,{\rm K}$.

However, He overabundances *are* observed in some early B stars. This fact led Vauclair (1975) to suggest another means of concentrating trace elements in the stellar atmosphere. She pointed out that the diffusion velocity of neutral helium in hydrogen is roughly two orders of magnitude larger than the diffusion velocity of ionized He. Now suppose that He becomes predominantly neutral in or just below the atmosphere, and that non-turbulent mass loss involving the dominant hydrogen component of the atmosphere is present. If the stellar wind occurs at such a rate that the upward velocity of H is larger than the downward diffusion velocity of ionized He below the atmosphere, but smaller than the very much greater downward diffusion velocity of the neutral He in the atmosphere, then the effect of the wind will be to sweep helium upward into the atmosphere because the wind transports the ions more rapidly than they can diffuse downward. In the cooler atmosphere, however, where He is neutral and its much larger downward diffusion velocity exceeds the upward wind velocity, the atom diffuses downward. Thus He accumulates in the atmosphere, to an extent which is limited by one of the competing mechanisms mentioned above. Computations (Vauclair et al 1991; hereafter VDG) have shown that this mechanism is capable of supporting an overabundance of He in or just below the atmosphere of a B star if a wind of the right magnitude (about $10^{-14}\ {\rm M_\odot\,yr^{-1}}$) occurs. Furthermore, VDG have pointed out that in lower mass A stars, where the accumulation of He due to such a wind would be well below the visible layers of the atmosphere, the expected accumulation would have another important effect: the excess He opacity would be expected to excite pulsations, perhaps those observed in the rapidly oscillating Ap stars (e.g. Kurtz 1990), by the $\kappa$ mechanism.

The stellar wind which is required for this mechanism to function is exceedingly hard to detect directly. Lanz & Catala (1992) derived from H$\alpha$ profile measurements some observational upper limits on possible winds in a few bright A stars of roughly $1\,10^{-10}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, far larger than the rates needed to produce abundance excesses supported by wind levitation. Other direct observational limits are similar in magnitude (Lanz & Hubeny 1993). Babel (1992) and Babel & Lanz (1992) present evidence (from differences in abundances of a single element derived from spectral lines in regions of differing continuous opacity) for vertical stratification of Ca and Cr in the cool magnetic Ap star 53 Cam, which they argue is consistent with wind-supported diffusion into the atmosphere of this star. However, competition between gravitational settling and radiative levitation could also lead to abundance gradients in the atmosphere, so this is not a clear test of the existence of a weak wind.

In this situation it is of great interest to identify further tests of the presence of weak winds in main sequence A and late B stars. One such test may be provided by searching for significant overabundances of elements of high natural abundance, such as C, N, O, or Ne, for which substantial overabundances are not expected to be produced by radiative levitation. A wind of order $10^{-14}$ to $10^{-12}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, if it is sufficiently quiet to allow diffusion to occur in and above the atmosphere, should concentrate these elements around the level at which they change from neutral to ionized form, just as occurs for He in the He-strong stars around $T_\mathrm{e} \sim 20,000\,\mathrm{K}$. Now the particular interest of these other abundant elements is that they have lower first ionization potentials than He. Accumulation of these elements due to a wind would occur at lower temperature, thus at a higher level in the stellar envelope than the region in which He should accumulate. An accumulation layer could thus occur in the visible photosphere of a star in which He would accumulate at too great a depth to be visible. We thus may hope to use the elements C, N, O, and Ne as probes of the presence of weak winds in stars too cool to reveal these winds by accumulation of excess He in the photosphere. *Detection of substantial overabundances of these already cosmically abundant elements could thus provide a sensitive and reasonably unambiguous means of detecting the occurrence of weak stellar winds in late B and early A type stars.*

In this paper we explore the potential utility of this means of searching for weak winds in late B and A main sequence stars. In the next section, we examine the order of magnitude of various quantities involved, to establish approximately the range of effective temperatures over which particular elements may serve as useful probes, and the range of mass loss rates which would be expected to lead to observable overabundances. In Sect. 3, we estimate the radiative accelerations of O and Ne in a variety of stellar envelopes, an exercise which provides us with values for $g_\mathrm{R}$ to use in subsequent calculations, and which also confirms that radiative accelerations are unlikely to be able to produce overabundances of either of these elements in the atmosphere of a middle main sequence star. In Sect. 4, we present the results of some numerical calculations under plausible conditions of the net vertical velocities that might result from the competition between downward diffusion and mass loss, for several specific cases. Sect. 5 considers the effects of processes that may compete with diffusion and wind levitation. In Sect. 6, we examine available stellar abundance studies to see whether their results suggest the occurrence of winds with mass loss rates in the range to which this test is sensitive, and in Sect. 7 discuss the relationship of wind accumulation to theories of chemical peculiarities.

**Table 1.** Elements of high abundance in the sun

| Z | Element | X(Z) | $\chi_{01}$ (eV) | useful $T_\mathrm{e}$ range (K) |
|---|---|---|---|---|
| 2 | Helium | $2.75\,10^{-1}$ | 24.48 | 14000 - 20000 |
| 8 | Oxygen | $9.53\,10^{-3}$ | 13.56 | 8500 - 11000 |
| 6 | Carbon | $3.03\,10^{-3}$ | 11.20 | below 8500 |
| 26 | Iron | $1.84\,10^{-3}$ | 7.86 | |
| 10 | Neon | $1.70\,10^{-3}$ | 21.47 | 11000 - 16000 |
| 7 | Nitrogen | $1.08\,10^{-3}$ | 14.49 | 8000 - 11000 |

## 2. An exploratory survey of the situation

In this section, we estimate the ranges of stellar effective temperatures and mass loss rates which could produce overabundances of one or another of the naturally abundant elements in observable levels of the atmosphere by wind levitation.

In Table 1, we list the potentially interesting elements. This table gives the mass fraction $X(Z)$ in the sun of all elements heavier than H that contribute a mass fraction in excess of $1\,10^{-3}$ (Anders & Grevesse 1989). The third column gives the first ionization potential $\chi_{01}$ for each element. The last column will be explained below. These elements satisfy the condition of having such high abundances in a solar mix that large overabundances are not expected to be produced by radiation forces below about $T_\mathrm{e} = 15000\,\mathrm{K}$. An observed overabundance should be a reasonably unambiguous symptom of a weak stellar wind.

The elements in Table 1 fall into three groups. He and Ne have ionization potentials near 23 eV, and thus make the neutral-ion transition at a temperature around 15,000 K. C, N and O all have first ionization potentials near 13 eV, and thus make the neutral-ion transition a temperature near 9000 K. Fe has such a low ionization potential that it is predominantly neutral only in cool stars. Thus He and Ne are elements that could be indicators of a wind in B stars, while C, N and O may be useful probes for early A stars.

We may estimate the range of usefulness in $T_\mathrm{e}$ of the various ions as follows. We calculate the ionization equilibrium of ions of interest for tabulated model atmospheres with a range of $T_\mathrm{e}$. From these data, we estimate the lower effective temperature limit of the usefulness of a particular element by requiring that the neutral-ion transition, where the accumulation is expected to occur, be no deeper in the atmosphere than $\tau_{5000} \sim 2$. Accumulations at a deeper level may not be detectable in the visible spectrum. The upper temperature limit will be set by the requirement that the element in question be significantly neutral ($n(Z_+)/n(Z_0) \leq 1$) somewhere in the atmosphere, so that downward diffusion of a substantial fraction of the atoms of the element in question is possible with the relatively large velocity of neutrals.

The results of numerical evaluation of these criteria using Kurucz (1979) atmospheres of $\log g = 4$ are given in the fifth column of Table 1. For He and Ne, the range of potential usefulness is approximately as expected. The small difference in ionization potential between these two elements leads to a significant difference in effective temperature range over which each may serve as a wind indicator, but there is overlap near 15,000 K. For the atoms of lower ionization potential, the range of potential usefulness is about as expected for N and O, while the slightly lower ionization potential of C makes it useful only at relatively low temperature, below $T_{\rm e} \sim 8500$ K.

It thus appears that the most interesting ions from the point of view of detecting a weak wind in B and early A stars are He and Ne, which cover the temperature range from about 11,000 K to 20,000 K, together perhaps with O and N, which should be sensitive in a more limited temperature range between 8000 and 11,000 K. It is unfortunate that not much overlap of the useful range of these elements as wind probes seems to occur; only one or two elements are effective probes at any particular temperature. However, it is interesting that He should be a spectroscopically useful probe of a weak wind at effective temperatures substantially lower than the lowest temperature (about 18,000 K) at which He-strong stars have been observed; this may mean that winds in the appropriate range of mass loss are rare below 18,000 K, or that they are too turbulent to permit atmospheric separation.

We next estimate the range of wind strengths over which two representative ions, Ne and O, may be useful as probes of wind strength. As described above, the weakest wind that will be detectable using one of the probe ions is one in which the upward wind velocity of the hydrogen, $v_{\rm w}$, in the region in which the probe atom is ionized is only a little larger than the downward diffusion velocity $v_{\rm d}$. The strongest detectable wind will be one in which $v_{\rm d}$ in the atmosphere where the probe atoms are neutral is only a little larger than $v_{\rm w}$. We may get a rough estimate of the range of detectable mass loss rates as follows. The mass flux through the various layers of the envelope and atmosphere of the star is assumed not to vary significantly with depth (i.e., the outflow of the dominant H constituent is assumed to be in a steady state). With this assumption, the global mass loss rate $\dot{M}$ is related to the density $\rho$ and to $v_{\rm w}$ at a radial position $r$ in the envelope of the star by

$$\dot{M} = 4\pi r^2 \rho v_{\rm w}. \quad (2)$$

In the outer envelope, roughly in the outer $10^{-4}$ of the stellar mass, $r \approx R$, where $R$ is the stellar exterior radius, and so the product $\rho v_{\rm w}$ is nearly constant. It will be convenient to compare this quantity to the same quantity $\rho v_{\rm d}$ calculated for the diffusion velocity $v_{\rm d}$. Numerically,

$$\rho v_{\rm w} = 1.04\,10^{-11} \dot{M}_{-14} (R/R_{\odot})^{-2}\,{\rm gm\,cm^{-2}\,s^{-1}}, \quad (3)$$

where $\dot{M}_{-14}$ is the mass loss rate in units of $10^{-14}\,{\rm M_{\odot}\,yr^{-1}}$.

The diffusion velocity of the elements considered is computed using the Chapman & Cowling (1970) approximation for trace elements diffusing in partially ionized hydrogen. At the low densities involved, the corrections proposed by Paquette et al (1986) lead to small effects. The diffusion velocity $v_{\rm d}$, neglecting collisions with He and turbulent diffusion, is then

$$v_{\rm d} \approx D[-\nabla \ln c_i + \frac{A_i m_{\rm A} g_{\rm R}}{kT} + k_T \nabla \ln T - \left( (A_i - 1) + (A_i - Z_i) \frac{n_{\rm H1}}{n_{\rm H0} + n_{\rm H1}} \right) \nabla \ln P] \quad (4)$$

Here $D$ is the diffusion coefficient, the number densities of neutral and ionized H are $n_{\rm H0}$ and $n_{\rm H1}$, $c_i$ is the concentration of trace ion $i$ [$c_i \approx n_i/(n_{\rm H0} + n_{\rm H1})$], $A_i$ and $Z_i$ are the atomic mass number and net ionic charge (N. B. *not* nuclear charge) of the trace ion, $g_{\rm R}$ is the radiative acceleration of ion $i$, $k_T \approx 2.65 Z_i^2 - 0.804 Z_i$ is the thermal diffusion coefficient (Montmerle & Michaud 1976), and other symbols have their usual meanings (Vauclair 1983). The term containing $(A_i - Z_i)$ makes the equation tend to its two correct limiting forms for predominantly neutral or predominantly ionized H.

The diffusion coefficient $D$ is an average over the various interactions that ion $i$ can undergo. Interactions with neutral or ionized H usually dominate. The different interactions of a particular ion of a given element are combined by adding the interaction frequencies of the various processes. For interactions between ions, the diffusion coefficient is given approximately by

$$D \approx \frac{1.95\,10^{19} T_4^{5/2}}{n_{\rm H1} Z_i^2 A_1(2)} \left( \frac{A_i + 1}{A_i} \right)^{1/2} {\rm cm^2\,s^{-1}}, \quad (5)$$

where $T_4 = T({\rm K})/10^4$ is the temperature in units of $10^4$ K, $A_1(2) = \ln(1 + x_i^2)$, and $x_i^2 = 2.732\,10^{20} T_4 / Z_i^2 n_{\rm e}$ (Chapman & Cowling 1970). In the case of a neutral trace atom diffusing through ionized H, the diffusion coefficient is approximately

$$D \approx \left( \frac{1.04\,10^{21} T_4}{n_{\rm H1} \alpha_{-25,i}^{1/2}} \right) \left( \frac{A_i + 1}{A_i} \right)^{1/2} {\rm cm^2\,s^{-1}}, \quad (6)$$

where $\alpha_{-25,i}$ is the polarizability of the trace atom in units of $10^{-25}\,{\rm cm^3}$ (Michaud et al 1978). For an ion diffusing in neutral H, we use the same expression, with $\alpha_{-25,{\rm H}} = 6.70$ as the polarizability of neutral H (e.g. Allen 1973). Finally, for a neutral atom moving in predominantly neutral H, we use the hard-sphere expression

$$D \approx \frac{5.44\,10^{21} T_4^{1/2}}{n_{\rm H0} (\delta_{\rm H} + \delta_i)^2} \left( \frac{A_i + 1}{A_i} \right)^{1/2} {\rm cm^2\,s^{-1}}, \quad (7)$$

where $\delta_{\rm H}$ and $\delta_i$ are the diameters of the atoms of H and of the diffusing species $i$ in Å (Vauclair 1983). Except for $n_{\rm H0}$ and

**Table 2.** Values of $\rho v_\mathrm{d}$ and corresponding mass loss rates

| Atom | $T_\mathrm{e}$ | $v_\mathrm{d}\rho$ ($\tau = 10$) | $v_\mathrm{d}\rho$ ($\tau = 0.01$) | $\dot{M}_{-14,\mathrm{l}}$ | $\dot{M}_{-14,\mathrm{u}}$ |
|---|---|---|---|---|---|
| Ne | 14,000 | $3.5\,10^{-12}$ | $2.1\,10^{-10}$ | 4.4 | 270 |
| O | 9,000 | $9.1\,10^{-13}$ | $2.4\,10^{-10}$ | 0.55 | 140 |

$n_\mathrm{H1}$, and $A_1(2)$ which generally is between 10 and 20, all the subscripted variables in these three equations are of order unity, and it is easily seen that the diffusion coefficient (and hence the diffusion velocity) is roughly two orders of magnitude smaller for an ion interacting with ionized H than for a neutral atom interacting with either neutral or ionized H at a given density and temperature.

We now estimate values of $v_\mathrm{d}$ (or of $v_\mathrm{d}\rho \approx v_\mathrm{d} m_\mathrm{A}(n_\mathrm{H0} + n_\mathrm{H1})$) for a few specific cases to determine approximately the range of mass loss rates which this method may reveal.

In Eq. (4), we ignore the concentration gradient, thermal, and radiative acceleration terms to estimate the limiting lower and upper mass loss rates. The smallest detectable mass loss rate, for which the upward wind velocity barely exceeds the downward diffusion velocity of ionized atoms below the stellar atmosphere, is estimated by applying the condition $\rho v_\mathrm{w} = \rho v_\mathrm{d}$ at $\log\tau = +1$. The maximum detectable wind, one for which the downward diffusion velocity barely exceeds the upward wind velocity in the atmosphere where the appropriate trace element is neutral, is estimated from applying the condition $\rho v_\mathrm{w} = \rho v_\mathrm{d}$ at $\log\tau = -2$. We make the estimates using a Kurucz (1979) atmosphere of $T_\mathrm{e} = 14000$ K for Ne, and one of $T_\mathrm{e} = 9000$ K for O. Diffusion coefficients are calculated considering only the single dominant contribution to $D$. We again take $\log g = 4$, and set $R/R_\odot = 3.6$ for the $T_\mathrm{e} = 14000$ K atmosphere, and $R/R_\odot = 2.5$ for the $T_\mathrm{e} = 9000$ K atmosphere (Maeder & Meynet 1988). The estimated values of $\rho v_\mathrm{d}$ and the corresponding lower $\dot{M}_\mathrm{l}$ and upper $\dot{M}_\mathrm{u}$ mass loss rates are given in Table 2. We see that mass loss rates expected to be detectable through wind accumulation lie roughly in the range of $10^{-12}$ to $10^{-14}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

## 3. Radiative acceleration

We next calculate approximate radiative accelerations for Ne and O. This will establish that radiative levitation is unimportant in the outer envelopes of stars in the range of effective temperatures in which these atoms could serve as wind probes, and will provide us with an estimate of the radiative accelerations to use below in detailed numerical calculations of the variation of diffusion velocity and flux with depth in four representative stellar envelope models. We make these estimates because no published accelerations are available for O for most of the range of conditions we consider, and none are available for Ne.

Vauclair (1983) summarizes the theory of the radiative acceleration given to an ion through a single spectral line. She gives expressions for both a Lorentzian line profile [her Eqs. (81) and (82)] and for a Gaussian profile [equation (85) and the easily derived analogue for an unsaturated line. (Note however that the numerical coefficient in her Eq. (85) is incorrect: it should be $3.73\,10^{-26}$ rather than $1.2\,10^{-26}$].) We use these expressions to estimate radiative accelerations.

The contribution made to the radiative acceleration by a single level of a particular ion may easily be seen from Vauclair's Eq. (79) to be equal to a factor independent of the atomic line's properties, times a frequency width $\Delta\nu_{line}$ which is rather close to the line width measured at the frequency points where the line wing opacity is equal to the continuum opacity. We estimate the value of $\Delta\nu_{line}$ for a Voigt profile by taking the larger of the values resulting from Vauclair's expressions for the Gaussian and the Lorentzian cases, interpolating smoothly between the two limiting cases of the Gaussian.

We treat the lines as isolated. Although the resonance lines of interest to us are generally in fairly closely spaced multiplets, it is found that the separations of the Ne lines are usually larger than the effective widths $\Delta\nu_{line}$ of the single lines. However, for O (mainly because of its higher cosmic abundance), many of the lines are more closely spaced than their individual effective widths. In this case our calculated radiative accelerations are a little larger than they would be if overlapping were treated correctly.

We consider only lines arising from the ground state or from excited states having lower energy level $E_\mathrm{l}$ satisfying $E_\mathrm{l}/\chi_{ii+1} \le 0.4$. This simplification is appropriate because we find quite generally that in the stellar models that we are using, the transition from ionization state $i$ to state $i+1$ is essentially complete at a temperature for which $kT/\chi_{ii+1} \sim 0.09$. This insures that for the neglected lines of ionization state $i$, the quantity $E_\mathrm{l}/kT = (E_\mathrm{l}/\chi_{ii+1})(\chi_{ii+1}/kT) \ge 0.4\,(1/0.09) = 4.4$, so that the Boltzmann population factor $exp(-E_\mathrm{l}/kT)$ for the neglected energy levels of ionization state $i$ is generally smaller than $1\,10^{-2}$. Consequently, the contribution of the neglected lines to the total radiative acceleration will not be important.

Neglecting all lines with $\log gf < -3$, we need of the order of 100 oscillator strengths for each ionization state of O and Ne to calculate the desired radiative accelerations. Most of the required data were obtained from R. L. Kurucz via a World Wide Web server at http://cfa-www.harvard.edu/amp/data/stats/kurucz.html. Additional data for the highest ionization states of both O ($O^{+6}$ and $O^{+7}$) and Ne ($Ne^{+6}$ though $Ne^{+9}$) were obtained from the Opacity Project data base described at http://astro.u-strasbg.fr/OP.html. (Opacity Project data give multiplet strength only, without fine structure. Transitions from this source were treated as single lines.) Radiative damping constants were estimated from the $gf$ values of the lines. Collisional damping constants were calculated using the semi-empirical approximation adopted by Alecian & Artru (1990; see also Gonzalez et al 1995a).

We have calculated numerically the radiative accelerations of Ne and O in four stellar model envelopes with parameters near those suggested as optimal for detection of an accumulation by the results in Table 1. The parameters of the stellar models used are shown in Table 3. They are essentially zero-age main sequence models, from the series that was previously used

**Table 3.** Stellar models

| $M/M_\odot$ | $T_{\rm e}$ (K) | $\log g$ | $R/R_\odot$ | $\dot{M}_{-14}(10^{-11})$ |
|---|---|---|---|---|
| 1.6 | 8000 | 4.30 | 1.477 | 2.10 |
| 2.0 | 9660 | 4.35 | 1.556 | 2.33 |
| 2.5 | 11530 | 4.43 | 1.594 | 2.44 |
| 3.0 | 13490 | 4.44 | 1.724 | 2.86 |

in discussing wind levitation of He by VDG. Table 3 includes, for later reference, the mass loss rate $\dot{M}_{-14}(\rho v_w = 10^{-11})$ in units of $10^{-14}\,{\rm M}_\odot\,{\rm yr}^{-1}$ corresponding to a wind flux of $10^{-11}\,{\rm gm\,cm^{-2}\,s^{-1}}$.

It is not necessary to calculate the radiative accelerations in the atmosphere to establish that accumulation cannot occur via radiative levitation. Radiative acceleration exceeding gravity within a stellar atmosphere cannot make excess atoms accumulate there (although the atoms may be redistributed in a manner that can mimic a mild overabundance); only radiative (or wind) levitation from below can bring excess trace atoms into the atmosphere. However, to ensure that atoms of O and Ne are not simply blown out of the stellar atmosphere by radiative levitation, making the present calculations irrelevant, it is worthwhile to estimate the order of magnitude of $g_{\rm R}$ in the atmospheres at hand to the extent that this is practical.

Calculation of $g_{\rm R}$ in the atmosphere of a star is in general much more complex than in the envelope because the diffusion approximation for the flux becomes very inaccurate: the temperature gradient tends to zero in the outer atmosphere, but the flux does not. Instead, the overlap integral of each spectral line with the actual emerging flux must be computed explicitly. However, for Ne in the models we consider, it is probably correct to use the diffusion approximation throughout the atmosphere. This is because all the lines of Ne I having lower level below $0.77\chi_{01}$, and all those of Ne II with lower level below $0.65\chi_{12}$, have wavelengths shortward of the H Lyman limit. Since the entire atmosphere that we consider here (out to $\log\tau_{5000}\sim -2$) is optically thick in the Lyman continuum, all these low-lying lines can be treated in the diffusion approximation even in the stellar atmosphere. Line arising from higher-lying levels, which see a larger flux because they occur at wavelengths for which the atmosphere is optically thin, nevertheless have Boltzmann factors of less than $10^{-3}$ by the argument described above. We assume that these lines will not contribute an important radiative acceleration, and ignore them.

For O I this convenient circumstance does not occur. We have therefore estimated a very rough upper limit to the radiative acceleration on O in each stellar atmosphere by assuming that each line longward of the Lyman limit absorbs at every depth continuum flux (computed as black-body radiation for $T = T_{\rm e}$) over one thermal line width with the opacity coefficient at line centre. Since this approximation ignores all self-shadowing in these lines (which generally have optical depths of order $10^3$), our estimate probably greatly overestimates the actual radiative acceleration. [Compare this approximation with that of Castor et al (1975), Eq. (1).] However, even with this approximation, $\log g_{\rm R}$ never significantly exceeds 4.0 in any of our atmospheres.

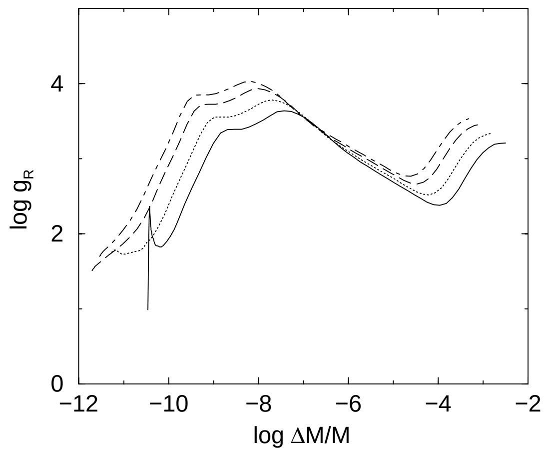


**Fig. 1.** Radiative acceleration $g_{\rm R}$ of O as a function of depth in the stellar envelope as measured by $\Delta M/M$, for solar O abundance. The four curves are for the four envelope models used for our calculations, namely 1.6 $M_\odot$ (solid line), 2.0 $M_\odot$ (dots), 2.5 $M_\odot$ (dashes), and 3.0 $M_\odot$ (dash-dots).

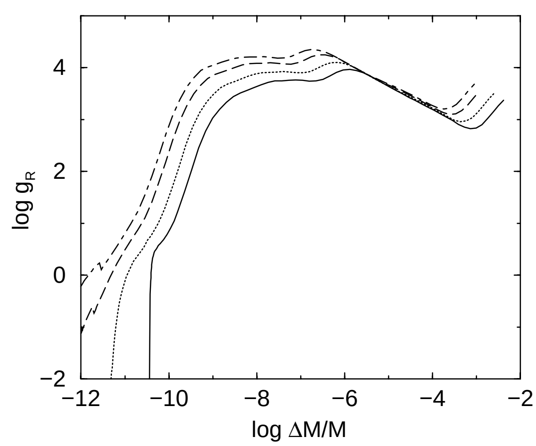


**Fig. 2.** Same as Fig. 1, but for Ne.

The calculated variations of $g_{\rm R}$ as a function of external mass fraction, $\Delta M/M$, are shown in Figs. 1 and 2. For O the calculations are cut off at approximately $T = T_{\rm e}$, while for Ne they are carried throughout the atmosphere.

In Fig. 3 we compare the variation of $g_{\rm R}$ with depth in the 1.6 $M_\odot$ model, which has $T_{\rm e}$ = 8000 K and $\log g$ = 4.30, with the more accurate calculations carried out by Gonzalez et al (1995b) for O in a stellar envelope model with $T_{\rm e}$ = 8000 K, $\log g$ = 4.20. Considering the approximate nature of our method, the two results are very similar, and give us confidence in the accuracy of the rest of our radiative accelerations. Over almost the full region of overlap, the two results differ by only about 0.1 to 0.2 dex.

A similar comparison with envelope $g_R$ calculations recently completed by Turcotte et al (1997) for both Ne and O for a star very similar to our lowest mass star also shows good general agreement.

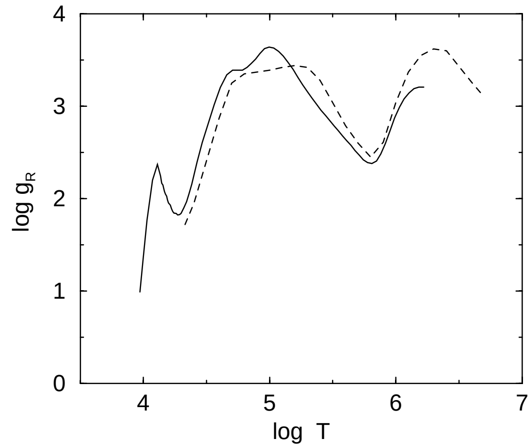


**Fig. 3.** Radiative acceleration of O calculated by our simplified procedure for the 1.6 $M_\odot$ model (solid line), compared to values calculated by Gonzalez et al for a very similar stellar model (dashed). For this comparison we use temperature $T$ as ordinate.

The $g_{\rm R}$ calculations shown in Figs. 1 and 2 have two interesting features. First, we find that even where the radiative accelerations are greatest (in levels below $10^{-9}$ or $10^{-10}$ M), the accelerations for solar abundance never exceed $g_{\rm R} \approx 1.5\,10^4$ cm s$^{-2}$. This is to be contrasted to calculations of radiative accelerations for less abundant elements, which often find values of $g_{\rm R}$ two orders of magnitude greater than the main sequence gravity ($3.5 \leq \log g \leq 4.5$). Thus, since the acceleration *decreases* with increasing abundance, nowhere in the regions we have examined are the radiative accelerations large enough to lead to substantial overabundances of either Ne or O. This is very reassuring; we originally chose to look at these relatively abundant elements precisely because it seemed unlikely that they would be radiatively levitated to any important extent.

Secondly, the radiative acceleration in shallower regions of the stellar models, above about $10^{-9}$ or $10^{-10}$ of the total mass, are small compared to the main sequence gravity. The result of the very low accelerations found near the surface is that we do not expect radiative levitation to be able to produce overabundances of either O or Ne in visible layers of stars in this temperature range; in fact, if only gravity and radiation act, and no mixing occurs, both O and Ne should decrease in abundance in the atmosphere to values well below the normal solar abundance values before radiative levitation is able to balance gravitational sinking.

## 4. Numerical calculations of diffusion velocities

We next compute the variation of the vertical diffusion velocity in our stellar envelope models to confirm that the diffusion velocities and fluxes show the strong decrease from the atmosphere into the outer envelope that we have predicted in Sect. 2, and that the diffusion velocities remain at a low enough level throughout the stellar envelope to allow a stellar wind of the right magnitude to sweep a substantial overabundance of O or Ne into the layers close to the atmosphere.

For each of the four stellar envelopes described above, the diffusion velocity of Ne or O is computed at each level of the star as follows. Diffusion coefficients $D_{0i}$ and $D_{1i}$ are calculated for each ionization state $i$ for collisions with neutral H [using Eq. (6) or (7)] and with protons [using Eq. (5) or (6)]. Since the two diffusion coefficients for a particular ionization state are inversely proportional to collision frequencies, the total diffusion coefficient for state $i$ is

$$\frac{1}{D_i} = \frac{1}{D_{0i}} + \frac{1}{D_{1i}}. \tag{8}$$

Collisions with He, which contributes about 10% of the scattering particles in the gas, are neglected.

The diffusion velocity of each significant ion of the element of interest is then computed from the diffusion Eq. (3). Because we are interested in the initial situation, the concentration term is neglected. The upward radiative acceleration is taken from the calculations of the previous section. In the atmospheres of these models, radiative acceleration is included in the calculation of $g_{\rm R}$ for Ne, for which we have reasonably accurate values, but is set to 0 for O, for which we have only rough upper bounds. The atomic diameters needed in Eq. (7) are taken to be twice the radial expectation value $< R >$ from Table 3 of Desclaux (1973) (1.0 Å for Ne, 1.3 Å for O, 1.6 Å for H). The polarizabilities $\alpha_{-25,i}$ required for Eq. (6) are taken from Teachout & Pack (1971) (3.96 for Ne, 7.7 for O, and 6.70 for H). The diffusion velocity of a trace element is taken to be the weighted mean of the diffusion velocities of individual ionization states.

The variation of $\rho v_{\rm d}$ is shown in Fig. 4 (for O), and Fig. 5 (for Ne). The five open dots along each curve indicate the depths at which the logarithmic optical depth is equal to -1, -0.5, 0, 0.5, and 1 as measured at 6150 Å for O, and 6500 Å for Ne; these are wavelengths which are convenient for observing lines of the element in question. Regions on each curve plotted with thicker lines indicate layers where (assuming uniform He abundance with depth) our stellar models are unstable to convection according to the Schwarzschild criterion. In all models, the convection layer at the greatest depth is where singly-ionized He is becoming doubly ionized; in the two lower mass stars, the shallower level is due to a combination of ionization of neutral H and of neutral He, while in the two more massive models, in which H is appreciably neutral only above $\tau \approx 1$, the outer zone of convective instability is due to the ionization of neutral He.

The calculations clearly show the rapid decrease of the downward diffusion flux of O and of Ne with depth, as predicted in Sect. 2. The only real exception is the case of O in the 3.0 $\rm M_\odot$ model, in which only a small variation in the diffusive flux $\rho v_{\rm d}$ with depth is found; in this model, O is more than 93% ionized everywhere in the atmosphere, and the rapid downward diffusion of the few neutral atoms is insignificant compared to the much slower diffusion of the ionized majority. In all other cases computed, the diffusive flux varies by at least two orders of magnitude between the atmosphere and deeper regions in the star. The fact that the change in diffusive mass flux is about two dex means that a mass loss rate anywhere within a correspond-

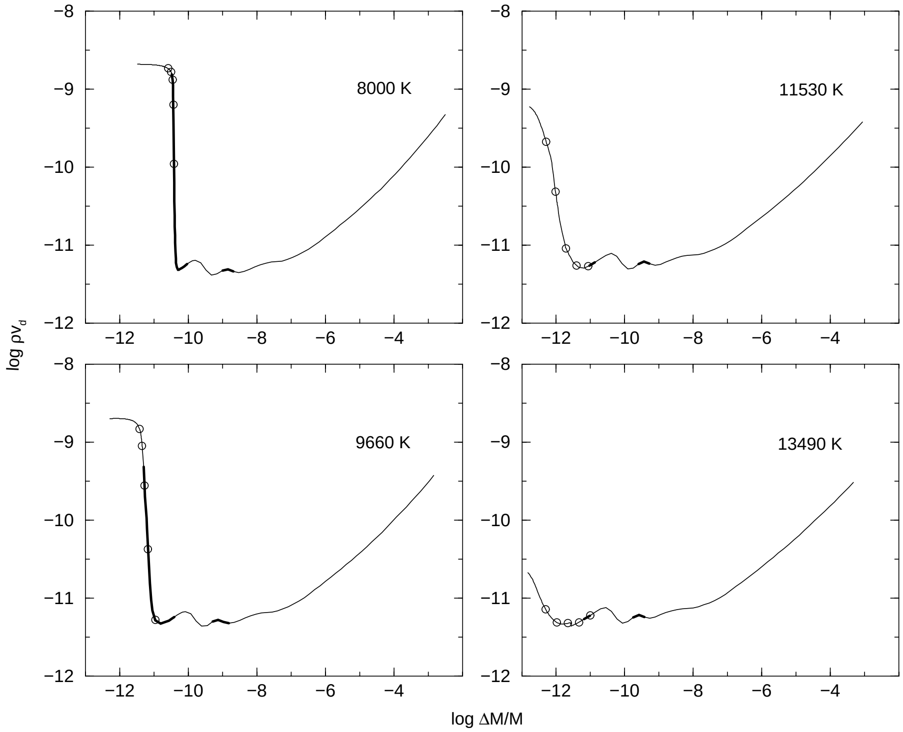


**Fig. 4.** Diffusion flux $\rho v_{\rm d}$ for O as a function of depth in the stellar envelope (measured by $\Delta M/M$) for each of the four stellar envelopes studied. On each curve, open dots show the locations of $\log\tau$ of -1, -0.5, 0, 0.5, and 1, measured at 6150 Å. Regions along each curve in heavier lines are convectively unstable according to the Schwarzschild criterion.

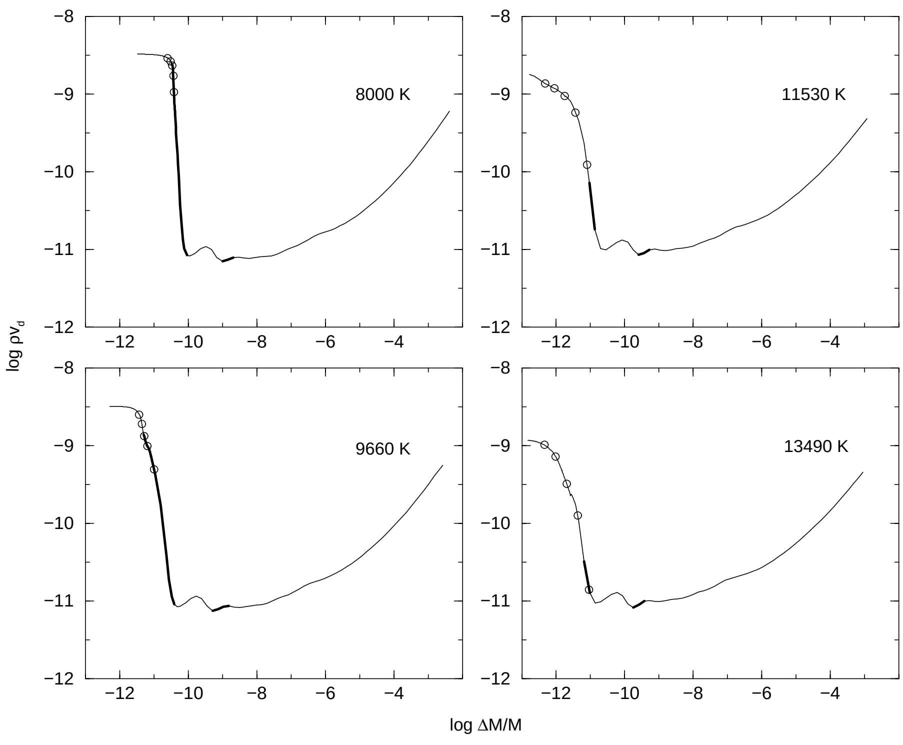


**Fig. 5.** As in Fig. 4, but for Ne. The locations of $\log\tau$ = -1, -0.5, 0, 0.5, and 1 are given for 6500 Å.

ing two dex range, for these models roughly between $10^{-14}$ and $10^{-12}\ {\rm M}_\odot\ {\rm yr}^{-1}$ (see Eq. (3) above, and the last column in Table 3) is expected to lead to an accumulation at roughly the level where the downward diffusion velocity is equal to the upward velocity of the wind. Thus, the fundamental idea of this paper, that competition between a stellar wind which is non-turbulent in and above the photosphere and downward gravitational diffusion should lead to accumulation of such abundant trace elements as Ne and O in layers not far below the atmosphere, appears to be confirmed by calculation.

Furthermore, the numerical calculations agree approximately with the estimates of which ions would be visible at what temperatures. In the 8000 K (1.6 ${\rm M}_\odot$) model, the region of rapid change of diffusive flux lies just a little below the region of optical depth unity for O, but well below for Ne. An accumulation of O at this effective temperature might be detectable, but an accumulation of Ne would probably not be (quite apart from the lack of observable Ne lines in the visible at this $T_\mathrm{e}$). In the model with $T_\mathrm{e} = 9660\,\mathrm{K}$ (2.0 $\mathrm{M}_\odot$), the O accumulation region would be in or just below the atmosphere. That of Ne would still not be detectable. At $T_\mathrm{e} = 11530\,\mathrm{K}$ (2.5 $\mathrm{M}_\odot$), O would accumulate above $\tau_{6150} = 1$, where it would certainly be detectable; the Ne accumulation region could still be below optical depth 1, but the increasing strength of the red Ne I lines would probably make detection possible. Finally, at $T_\mathrm{e} = 13490\,\mathrm{K}$ (3.0 $\mathrm{M}_\odot$), for O the high degree of ionization everywhere in the atmosphere leads to very small variations of the diffusion flux with depth, so that no accumulation is likely to occur; for Ne, the probable accumulation zone is in or close to the atmosphere.

Thus, the numerical calculations confirm the estimates presented in Table 1 of the range of $T_\mathrm{e}$ over which detectable accumulations of the trace ions O and Ne could occur, and to support the qualitative picture constructed in the preceding sections. (Recall that we have assumed that the wind is sufficiently quiescent to allow atmospheric diffusion to occur; if the wind is strongly turbulent in and above the photosphere, no separation or accumulation will occur. However, the existence of He strong stars, in which atmospheric accumulation of He by this mechanism is believed to occur, indicates that quiescent winds are possible.)

As a next step, one would like to compute the evolution of the abundance accumulation in the envelope or atmosphere of these models for a few plausible mass loss rates, as was done by VDG for He. We have not caried out such calculations because of a fundamental physical uncertainty in how to do this in a realistic manner. The problem concerns the mechanism that limits the accumulation of the trace ion. If an ion accumulates in a particular layer as we envisage here, the concentration will grow steadily with time. Although the growth will be opposed by the concentration gradient term of Eq. (4), this will not be the strongest limiting effect. Instead, as discussed by VDG, an analogue of thermohaline convection is expected to occur in stars without magnetic fields. It is not known at present how to estimate the effects of this process. In magnetic stars, this instability is impeded by the stiffening effect of the field, but some perhaps milder mixing process is certainly expected to occur which will limit the accumulations. Because we do not know how to model this effect realistically, it is usually treated as a parameterized diffusion with a diffusion coefficient which is extremely uncertain in size. As a result, calculations following the evolution of trace ion accumulations are illustrative at best, and cannot be presumed at present to have much predictive power. In this exploratory paper we limit ourselves to identifying regions where substantial accumulations should occur, but do not try to follow the accumulation process in detail.

## 5. Effects of convection, turbulence and ambipolar diffusion

We next consider the effects of convection in slowly rotating stars (i.e. stars without important rotational mixing). All of the models considered have two separate convective regions according to the Schwarzschild criterion (cf Figs. 4 and 5). These two layers are very likely joined by overshooting into one continuously mixed layer which probably extends somewhat deeper in the stellar envelope than the region indicated by the Schwarzschild criterion (Latour, Toomre & Zahn 1981; Freytag, Ludwig & Steffen 1996).

The effects of the convective layer(s) may be qualitatively assessed. Consider first the situation with no stellar wind. As long as the He abundance in the envelope layers where convection occurs is high enough to keep the instability active, the chemical abundances throughout the mixed region are uniform from top to bottom. For our two lower mass models, the mixed region will include much of the visible atmosphere; for the two more massive models, the mixed region may not reach as high as optical depth unity. However, in all cases the bottom of the (lower) convective zone is expected to reach a depth where the radiative accelerations of both O and Ne are comparable to main sequence gravity, and thus where radiation should support an abundance of each of these elements comparable to the solar abundance. It thus seems likely that the effect of convection will be to maintain an abundance of these two elements throughout the outer envelope, and probably in the stellar atmosphere, not far from the solar value. However, because the radiative acceleration for solar abundances is not significantly greater than the gravitational acceleration at the base of the convective zone, we do not expect to find an overabundance of either element even in the hottest model that we consider.

In the absence of a stellar wind, this initial situation is expected to change with time. Because a solar abundance of He is not supported by radiative acceleration anywhere in any of the model stellar envelopes we consider, even below the convectively unstable regions, He will gradually settle by diffusion below the unstable layers. In turn, the He in the unstable region will be slowly reduced as gas in the convective layer is gradually exchanged with gas in the stable layer below, until the abundance of He is too low to produce convective instability (Vauclair et al 1974). At this time, the convection will cease, and the O and Ne will begin diffusing downwards. At some later time, we expect to find atmospheric abundances of both species to be well below the solar values. Thus, in the absence of a stellar wind, we still expect that atmospheric abundances of the tracer ions considered here will be near or below solar values, as will be the case in the absence of convection.

If mass loss of H is added to the situation discussed above, the outcome is quite different. If the wind has a mass loss rate of more than about $10^{-14}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$, then levitation of He, O and Ne into the convective zone from below will occur (see Sect. 2 above and VDG), and the abundances of all three elements are expected to be at least solar. If the wind is within appropriate limits, but quiescent enough for separation above the atmosphere to take place, accumulation of He, O and Ne in and near the atmosphere is expected to occur as described in VDG and above. However, the accumulation will be spread throughout the unstable region, and hence the atmospheric abundances will grow more slowly than in the absence of convection. Still, we expect substantial overabundances to develop after a time $t$ large enough that the mass of some trace element A levitated by the wind into the mixed zone, $\epsilon_{\rm A}\rho v_{\rm w} 4\pi R^2 t$, is larger than the mass of that element initially in the mixed zone, about $\epsilon_{\rm A}(\Delta M/M)M_*$. For a mixed mass fraction $(\Delta M/M) \sim 10^{-9}$ and a wind flux $\rho v_{\rm w} \sim 10^{-10}$ g cm$^{-2}$ s$^{-1}$, the time required to increase the abundances in the convective region substantially is not much larger than $t \sim 10^4$ yr. Thus again we come to the conclusion that a moderate mass loss rate will lead to accumulation of our trace elements in visible layers of the model stars we consider, as was the case when convection was ignored, provided that the mass loss is sufficiently non-turbulent above the convection zone for gravitational settling to occur; a star without mass loss will not have an excess of either O or Ne in the atmosphere.

If the mass loss rate is substantially larger than $10^{-12}$ M$_\odot$ yr$^{-1}$, then levitation by the wind will overwhelm diffusion at all depths, and no accumulations will occur. Atmospheric abundances will be essentially solar.

In a rapidly rotating star ($v_{\rm equat} \geq 100$ km s$^{-1}$), we must also consider the effect of the meridional circulation. This flow, which slowly mixes envelope material into the outer layers of the star, may well be turbulent, enhancing its mixing abilities to an uncertain extent. In a rapidly rotating star, the degree of mixing will probably be sufficient to maintain essentially solar abundances in the atmosphere regardless of the presence or absence of a wind. The circulation will presumably prevent the settling of He, so that any convection zones will remain intact. In rapidly rotating stars, it appears that we are unlikely to detect the presence of a weak wind from accumulations of Ne or O.

Finally, consider the effects of ambipolar diffusion of protons with respect to neutral H in regions of partial H ionization. As shown by Babel & Michaud (1991b), if convection can be inhibited, relative diffusion of protons with respect to the the less interactive neutrals can sweep trace ions upward through the zone of partial H ionization. In a non-magnetic star, the zone of partial ionization in which p–H diffusion occurs coincides with the convection zone, so that rapid mixing prevents significant segregation of trace ions. However, in magnetic Ap stars, the convection may well be inhibited by the strong magnetic field. In this case, at least in regions of roughly vertical field (in a horizontal field, the p–H relative diffusion is inhibited), trace ions such as O and Ne could be swept upward through the zone of partial H ionization. This would lead to significant atmospheric accumulation of O and Ne for atmospheres having $T_{\rm e} \leq 10,000$ K. Between 10,000 11,000 K, the zone of partial ionization is so close to the atmosphere that only a small excess number of trace ions can be "mined" in the invisible region below $\tau_\nu = 1$, and above 11,000 K H is largely ionized throughout the atmosphere. Thus ambipolar diffusion of H *might* mimic the effect of a weak wind in causing detectable excess atmospheric accumulation of O at the low $T_{\rm e}$ end of the useful range of O in magnetic stars (Ne is not detectable at such low $T_{\rm e}$). However, ambipolar diffusion will not be a significant effect above 10,000 K.

## 6. Observed abundances of Ne and O

Given the predictions of the preceding sections, it is of interest to see whether the kinds of overabundances that we consider to be symptoms of a stellar wind have actually been observed in any of the middle main sequence stars for which chemical abundances have been determined.

The number of determinations of abundances of Ne in B stars is remarkably small. We have found modern abundance determinations for only six B stars around the temperature range of interest to us. The abundance of Ne in three B3–B5 IV stars (with $16,000 \leq T_{\rm e} \leq 18,000$ K, close to the upper limit of temperature for which we expect atmospheric accumulations to be possible) was discussed by Auer & Mihalas (1973). The stars they examined show approximately solar abundances of Ne. Abundances of Ne in three B5–B8 stars ($13,000 \leq T_{\rm e} \leq 14,500$ K) have been reported by Adelman (1984). Two stars show solar Ne, but the star $\pi$ Ceti appears to have a Ne abundance of about ten times solar. Unfortunately, the measurement of $\pi$ Ceti is based on only one spectral line, and is thus quite uncertain. At present, there is not enough observational evidence to clearly indicate whether the kind of winds we discuss in this paper might be present in middle B stars.

The situation is considerably clearer concerning oxygen. The largest recent study of O in the spectral range of interest to us is reported by Gerbaldi et al (1989) and by van't Veer-Menneret et al (1989). These two studies furnish oxygen abundances for approximately 140 B and A stars, both normal and peculiar, based on the strength of the O I $\lambda$ 7773 triplet. The general pattern found by previous studies is confirmed. Normal A and B stars (in the effective temperature range of 7000–15,000 K) show O abundance close to solar, often slightly ($\sim +0.2$ dex) higher, but sometimes as much as 1 dex lower. Am stars ($7,500 \leq T_{\rm e} \leq 10,000$ K) have O abundances between $-0.2$ and $-1.3$ dex below solar; HgMn Ap stars (10,000 $< T_{\rm e} <$ 13,500 K) have [O/H] between 0.0 and $-0.8$ dex. Magnetic Ap stars never have O above the solar abundance; Ap Si stars ($T_{\rm e}$ between 10,000 and 16,000 K) range down to [O/H] $\sim -1.8$, while cooler Ap's having Sr, Cr, and/or Eu anomalies ($7,500 \leq T_{\rm e} \leq 12,000$ K) can have [O/H] anywhere from approximately solar to as low as $-2.6$. (Note that this result suggests that atmospheric accumulation of O due to ambipolar diffusion in magnetic stars, as discussed above, also does not actually occur.) These results are confirmed by other studies, such as that of Roby & Lambert (1990).

Thus we find very little evidence among late B or A stars having $T_{\rm e} \leq 11,000$ of winds of the strengths to which O would be a sensitive tracer. We conclude that neither normal or peculiar stars with $8,500 \leq T_{\rm e} \leq 11,500$ generally have winds in the range of approximately $\dot{M} = 10^{-12} - 10^{-14}$ M$_\odot$ yr$^{-1}$, or if such winds are present, they must be too turbulent to allow diffusion to occur.

## 7. Discussion and conclusions

In this paper we have discussed how the presence of a weak stellar wind involving the loss of the dominant H component (and sufficiently non-turbulent in the photosphere to allow diffusion to occur), having a mass loss rate of the order of $\dot{M} = 10^{-12} - 10^{-14}$ $M_{\odot}$ yr$^{-1}$, would be expected to lead to the accumulation of an atmospheric overabundance compared to the normal solar value of some of the more abundant trace elements such as O, C, Ne and N, by the same mechanism proposed by Vauclair (1975) to explain excess He in the atmospheres of He-strong early B stars. The elements which would be expected to accumulate in visible layers depend on the effective temperature of the star, as indicated in Table 1.

We have considered Ne and O in more detail. For these two elements it is unlikely that an atmospheric overabundance could be produced by the action of radiative levitation. However, in the relevant range of effective temperature, if a stellar wind of the right strength occurs with little enough turbulence that diffusion in the atmosphere is possible, one expects to observe an overabundance of one of these trace elements. Similarly, the absence of overabundance of O (for $8,500 \leq T_{\rm e} \leq 11,500$) or Ne (for $11,000 \leq T_{\rm e} \leq 16,000$) implies that mass loss of H in the range $\dot{M} = 10^{-12} - 10^{-14}$ $M_{\odot}$ yr$^{-1}$ either is not occurring or is turbulent.

Observationally, there are not enough available Ne abundance determinations to reveal whether weak winds of the kind we have discussed are common, or indeed occur at all, in middle B stars. However, the data available for O suggest that such winds do *not* occur for stars having $8,500 \leq T_{\rm e} \leq 11,500$, or else they are turbulent above the convection zone. This result is interesting in connection with a mechanism proposed by Michaud & Charland (1986) to explain the occurrence of the abundance deficiencies that characterize the $\lambda$ Boo stars. They have shown that in an A or early F star, envelope diffusion in the region below the convection zone together with a modest mass loss rate ($\dot{M} \sim 10^{-13}$ $M_{\odot}$ yr$^{-1}$ by a fully mixed wind (i.e., one in which no separation of elements occurs) leads to gradual levitation into the convection zone of material from below which has been depleted in many trace elements, and thus to the development of a stellar atmosphere showing general underabundance with respect to the sun. They propose that this is the origin of the $\lambda$ Boo stars. However, our hypothesis is that separation in the wind of such a star should occur, and in particular lead to strong accumulation of O in the atmosphere. The most recent abundance studies of $\lambda$ Boo stars show either modest *under*abundances of O (Venn & Lambert 1990), or essentially solar value (Baschek & Slettebak 1988). No sign is found of the O accumulations that we predict should occur in the presence of a wind of this strength as a result of separation in the wind. It appears that either in stars this cool any wind is sufficiently turbulent to prevent element separation near the photosphere (presumably because of the convection in the outer envelope), or else the absence of an accumulation of O constitutes a serious problem for the model of Michaud & Charland.

Earlier, Michaud et al (1983) predicted that a still weaker unseparated wind (of the order of $\dot{M} \sim 10^{-15}$ $M_{\odot}$ yr$^{-1}$) would lead to a convection zone and photosphere which for most of the main sequence lifetime are enriched in trace elements. They propose this possibility as the origin of the Am phenomenon. Unfortunately, the mass loss rate that they require for this model is below the limit we expect to be detectable via atmospheric separation in the wind. We are unable to put any constraints on the occurrence of this process if it occurs with this small mass loss rate. However, recently Alecian (1996) has considered diffusion of Ca and Sr in Am stars with mass loss rates ranging from $0.5\,10^{-14}$ up to $5\,10^{-14}$ $M_{\odot}$ yr$^{-1}$. If these rates are correct, we would expect to find O overabundances in such stars, which are not observed. This appears to indicate that the mass loss rates assumed by Alecian are too high, or that in Am stars the wind is turbulent in and above the photosphere.

Babel & Michaud (1991a) have discussed the abundance distributions of several elements on the surface of the magnetic Ap star 53 Cam. They have shown that diffusive separation of elements in the atmosphere is by itself not able to account for the very strongly inhomogeneous distribution of some elements over the surface of the star, and have proposed that a H-rich stellar wind with a rate of $\dot{M} \sim 10^{-12} - 10^{-14}$ $M_{\odot}$ yr$^{-1}$, controlled by the strong magnetic field of the star (so that the mass loss would not be uniform over the stellar surface), could lead to the observed abundances. Babel (1992) has extended this model, and has shown that a mass loss rate of $\dot{M} \sim 3\,10^{-15}$ $M_{\odot}$ yr$^{-1}$ near the magnetic poles, and a substantially smaller rate around the magnetic equator, could lead to abundance inhomogeneities similar to those observed for some but not all of the elements for which observations of the abundance distribution are available. This mass loss rate is just at the lower limit of the mass loss rate for which we conclude that atmospheric accumulation of O will occur; it appears that absence of O accumulation in the atmosphere of this star would provide a limit on the mass loss rate which could be assumed for such a model. In fact, only one determination of the O abundance in this star seems to be available; Gerbaldi et al (1989) report an underabundance of $\sim -1.5$ dex for this star without giving the date of observation. However, O could well be variable over the surface of 53 Cam, and the one observation could have been made at a phase when the magnetic equator was in view, so this datum does not show that no O accumulation occurs anywhere over the star. Further observations could be interesting.

It thus appears that the accumulation (or not) of abundant trace elements in visible photospheric layers could indeed provide very interesting constraints on the occurrence or not of H-rich mass loss in a variety of physical circumstances where constraints on possible mass loss rates would be very useful defining possible parameter ranges for models of chemical abundance anomalies.

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