FLUORINE ABUNDANCES IN THE ORION NEBULA CLUSTER

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ABSTRACT

This is a pilot study using cool dwarfs as sources with which to probe fluorine abundances via HF. This molecule is detected for the first time in young K–M dwarf members of an OB association. The targets are three low-mass stars (JW 22, JW 163, and JW 433) belonging to the Orion Nebula Cluster. The target stellar parameters were derived to be $T_{\text{eff}} = 3650, 4250$, and $4400$ K and log $g = 3.5, 3.4$, and $3.6$, with corresponding stellar masses of $0.4$, $0.6$, and $0.7 M_\odot$, for JW 22, JW 163, and JW 433, respectively. Fluorine, oxygen, and carbon abundances were derived from the HF(1–0) R9 line along with samples of OH and CO vibrational-rotational lines present in high-resolution infrared spectra observed with the Phoenix spectrograph on the Gemini South Telescope. The fluorine and oxygen results obtained for these targets, still in the pre–main-sequence stage of evolution, agree well with the general trend defined for the Milky Way disk, the latter being deduced from observations of more evolved giant stars. In addition, the carbon and oxygen abundances obtained for the studied stars overlap results from previous studies of the more massive OB stars and FG dwarf members of the Orion Nebula Cluster. We conclude from this agreement that the fluorine abundances derived for the Orion K–M dwarfs (when there is no conspicuous evidence of disks) can be considered a good representation of the current fluorine abundance value for the Milky Way disk.

Subject headings: nuclear reactions, nucleosynthesis, abundances — open clusters and associations: individual (Orion Nebula Cluster) — stars: abundances

1. INTRODUCTION

The chemical elements are produced via a variety of nuclear and high-energy processes associated with stars of various masses, cosmic rays, and the big bang itself. One interesting process, whose importance within the overall scheme of nucleosynthesis is not yet well quantified, involves the inelastic scattering of neutrinos off of nuclei and is referred to as neutrino nucleosynthesis, or the $\nu$-process. Neutrino nucleosynthesis was discussed by Domogatsky et al. (1978), who focused mainly on its role in the production of the lightest elements, such as $^3$H, $^3$He, $^7$Li, or $^{11}$B. Later, Woosley & Haxton (1988) expanded on the role of the $\nu$-process in the production of fluorine, and subsequently Woosley et al. (1990) published predicted yields for a number of species, including Li and F. The neutrinos involved in the $\nu$-process are produced as a result of the gravitational collapse of a stellar core to a neutron star during a supernova of Type II (SN II). The $\nu$-process may result in significant synthesis of certain low-abundance isotopes that lie one mass unit below abundant nuclei, such as $^{12}$C, giving rise to $^{11}$B, or $^{20}$Ne, resulting in $^{19}$F via neutrino-induced spallation. It is the association of $^{19}$F, the only stable isotope of fluorine, with the $\nu$-process that makes its abundance of interest as a potential probe of neutrino nucleosynthesis.

In addition to the $\nu$-process, $^{19}$F is possibly produced during He-burning thermal pulses on the asymptotic giant branch (AGB), as first suggested by Forestini et al. (1992). Meynet & Arnould (2000) also pointed out that Wolf-Rayet stars, via the same sets of reactions as in the AGB stars, may also produce significant amounts of $^{19}$F, with the caveat that large $dM/dt$ stellar winds must remove a significant amount of mass, exposing the inner layers where fluorine is produced before it is burned away. Observations of fluorine abundances, spanning a range of stellar metallicities and across a variety of stellar populations, are needed in order to sort out relative contributions from AGB stars, Wolf-Rayet stars, or neutrino nucleosynthesis.

In this paper, we use high-resolution IR spectra from Phoenix on Gemini South to derive $^{19}$F abundances (from HF), along with $^{12}$C abundances (from CO) and $^{16}$O abundances (from OH), in three low-mass members of the Orion Nebula Cluster. Carbon and oxygen provide comparison abundances to those derived from fluorine. Both C and O have been studied previously in Orion members by Cunha & Lambert (1994); their study analyzed hot O and B stars. In addition, some oxygen abundances in Orion-member F and G main-sequence and pre–main-sequence stars have been published by Cunha et al. (1998). These previous studies provide a background on which the abundances derived from K- and M-type stars can be compared. Apart from the interest in the carbon and oxygen abundances in young stellar systems, C and O provide important comparisons for the fluorine abundances. The Orion Nebula Cluster stars are very young and will reflect the current Galactic F/O ratio in the disk. Also, previous stellar $^{19}$F abundances (derived from HF) have come only from red giants (Jorissen et al. 1992; Cunha et al. 2003), while here we undergo a pilot study to use cool dwarf stars as sources with which to probe fluorine abundances.

2. OBSERVATIONS

The target stars for this study are K and M dwarfs selected from various studies of the Orion Nebula Cluster by Hillenbrand (1997), Hillenbrand & Hartmann (1998), Hillenbrand et al. (1998), and Rhode et al. (2001). In particular, the stars were selected for high membership probability ($P \geq 93\%$), to be cool enough for the HF molecular line to be detectable ($T_{\text{eff}}$ of $<4500$ K), and to have relatively low values of projected rotational velocities.
Phoenix spectra are shown in Figure 1 for two of the target stars, with the two spectra shifted vertically in relative flux. The spectra plotted in this figure were obtained in the December 2002 Gemini run. The top panel shows the spectra in the $H$ band, while the bottom spectra are in the $K$ band. Some of the prominent absorption lines are identified in the figure, with the 15550 Å region showing a number of OH lines and the 23400 Å spectrum containing numerous $^{12}$C$^{16}$O lines.

### 3. STELLAR PARAMETERS

The effective temperatures for the studied stars were derived from their photometric colors $(V - I)$ and $(V - K)$ and by adopting the empirical calibrations from Bessel et al. (1998). $(V - I)$ and $(V - K)$ colors are considered to be good temperature indicators for cool stars and have little sensitivity to gravity for the effective temperature range considered in this study. The adopted photometric magnitudes are presented in Table 1. We obtained $V$ magnitudes and $(V - I)$ colors for our targets from the work by Hillenbrand (1997) that studied the stellar population comprising the Orion Nebula Cluster. The target star $K$ magnitudes were obtained from the Two Micron All Sky Survey (2MASS) database and corrected to the Bessel et al. system by means of the transformation equations presented in Carpenter (2001). Dereddened colors were computed by adopting $A_v = 0$ for JW 163, $A_v = 1.01$ mag for JW 433, and $A_v = 0.8$ for JW 22 (all values are taken from Hillenbrand 1997).

Surface gravities (log $g$ values) for the target stars were calculated from the following standard relation:

$$g/g_\odot = (M/M_\odot)(T_\text{eff}/T_\odot)^4(L/L_\odot)^{-1}.$$  

The stellar luminosities were taken from Hillenbrand (1997; log $L/L_\odot = 0.22, 0.43$, and $-0.34$ for JW 163, JW 433, and JW 22, respectively). These were derived assuming a distance to the Orion...
Nebula of 470 pc. As discussed in Hillenbrand (1997), the adopted stellar luminosities are estimated to have an uncertainty of 0.12 in log $L/L_\odot$. The effective temperatures adopted to derive log $g$ values were those listed in Table 1. Stellar masses could then be estimated from placement of the targets on an HR diagram and noting their position relative to evolutionary tracks computed by D’Antona & Mazzitelli (1994). Surface gravities were then computed for the sample stars. The derived masses and log $g$ values are presented in Table 1. From the uncertainties in the adopted stellar luminosities and effective temperatures we estimate that our derived surface gravities have a maximum uncertainty of about 0.27 dex.

4. ANALYSIS

LTE fluorine, carbon, and oxygen abundances were obtained from spectrum synthesis using the synthesis code MOOG (Sneden 1973). The model atmospheres employed in the analysis were calculated with the ATLAS9 code (Kurucz 1994) for solar metallicity, adopting a mixing length $l = 1.25 H_p$ and without convective overshooting.

4.1. Fluorine, Carbon, and Oxygen Abundances

Fluorine abundances can be derived from the vibrational-rotational lines of HF present in the spectral region around the $K$ band. In this study, we used the HF$(1{-}0) R9$ line at 23357.661 Å. In this same IR spectral window where HF was observed, several other molecular lines that correspond to $^{12}$C$^{16}$O first-overtone vibrational-rotational lines (3–1 vibration series) are also found, and these can be used to obtain the carbon abundances, given that the oxygen abundances are known from other transitions (such as OH). Synthetic spectra were calculated across the entire spectral region of the observed Phoenix spectra, or from $\sim$23340 to 23430 Å. The line list adopted was the same as in our previous study of fluorine in red giants of the Large Magellanic Cloud (see Cunha et al. 2003). The CO lines are typically used to derive the microturbulence in cool giants, where they are much stronger (such as in Smith et al. 2002). Although in the parameter range studied here the CO lines become weaker, they are still sensitive to the microturbulence and were used in order to estimate this parameter. The adopted values for the stars vary between $\xi = 0.5$ and 1.0 km s$^{-1}$ (Table 1).

Figure 2 shows the synthetic and observed spectra for all three target stars near the HF line. Three synthetic spectra, each with a different fluorine abundance, are plotted in each panel in order to illustrate the sensitivity of the HF line to the fluorine abundance. Just to the blue of the HF$(1{-}0) R9$ line is a stellar photospheric line that is probably due to H$_2$O. This same unidentified line is clearly visible (in the same approximate relative strength) in the solar sunspot spectrum published by Wallace & Livingston (1992). They identify a number of other H$_2$O lines in this spectral region that have similar strength. Water is not included in the synthesis line list here, and the offending line blends just a small fraction of the blue edge of the HF line and does not affect significantly the derived $^{19}$F abundance.

The final abundances derived for carbon, oxygen, and fluorine are presented in Table 1. The expected uncertainties in the

| Star    | $V_0$ | $I_0$ | $K_0$ | $T_\text{eff}$ | log $g$ | $\xi$ | $M/M_\odot$ | $A(\text{^{12}C})$ | $A(\text{^{16}O})$ | $A(\text{^{19}F})$ |
|---------|-------|-------|-------|---------------|--------|------|-------------|-----------------|----------------|------------------|
| JW 22   | 15.5  | 13.4  | 11.3  | 3650          | 3.6    | 1.0  | 0.4         | 8.40            | ...            | 4.61             |
| JW 163  | 13.1  | 11.8  | 10.2  | 4250          | 3.5    | 0.5  | 0.6         | 8.00            | 8.55           | 4.53             |
| JW 433  | 12.5  | 11.3  | 9.6   | 4400          | 3.4    | 0.8  | 0.7         | 8.30            | 8.80           | 4.65             |

Note.—$A(X) = \log [n(X)/n(H)] + 12$.
derived effective temperatures and surface gravities are 100 K and 0.3 dex, respectively. The errors in the microturbulence parameters are estimated to be around 0.5 km s\(^{-1}\). The sensitivity of the derived C, O, and F abundances to changes in temperature, gravity, and microturbulence for two target stars (the coolest and the hottest in our sample) are presented in Table 2; the total errors (\(\Delta A\)) in the derived abundances in each case are listed in the last column. Overall, the studied transitions of HF, CO, and OH are weak and relatively insensitive to the microturbulence, the exception being the CO lines, which are moderately strong at \(T_{\text{eff}}\) values around 3650 K. The fluorine abundances are mostly sensitive to effective temperature, but also, to a lesser extent, to the surface gravity. Concerning OH, the abundance errors are quite insensitive to changes in surface gravity and microturbulence. The total abundance errors for oxygen are dominated by \(T_{\text{eff}}\) uncertainties. (OH abundances were not calculated for JW 22 in this study.) The uncertainties in the derived carbon abundances are shown to have different sensitivities at the “cool” and “hot” regimes studied here. These are more uncertain around 3600 K when compared to 4500 K.

5. DISCUSSION

Our larger goal is to investigate the behavior of fluorine abundances with metallicity, which is taken here to be represented by the element oxygen, as this element is virtually a pure product of nucleosynthesis in massive stars that end their evolution as core-collapse SNe II. In particular, in this study we focus on the fluorine and oxygen contents of the pre–main-sequence stellar members of the Orion Nebula Cluster.

As mentioned in the introduction, carbon and oxygen abundances derived from molecular transitions (CO and OH) can be used as benchmarks with which to gauge the fluorine abundances obtained from HF. A comparison of carbon and oxygen abundances derived here for JW 22 and JW 433 with abundances from Cunha & Lambert (1994) and Cunha et al. (1998) is in order; we ignore JW 163 in this comparison as there is evidence that the absorption lines may be affected measurably by emission

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**Table 2: Abundance Uncertainties**

| Star   | Element | \(\Delta T_{\text{eff}} (+100 \text{ K})\) | \(\Delta \log g (+0.3 \text{ dex})\) | \(\Delta \xi (+0.5 \text{ km s}^{-1})\) | \(\Delta A\) |
|--------|---------|------------------------------------------|-----------------------------------|---------------------------------|-------------|
| JW 22  | C       | 0.08                                     | 0.0                               | 0.10                            | 0.13        |
| JW 22  | F       | 0.08                                     | 0.05                              | 0.0                             | 0.09        |
| JW 433 | C       | 0.15                                     | 0.15                              | 0.0                             | 0.21        |
| JW 433 | O       | 0.10                                     | 0.02                              | 0.0                             | 0.10        |
| JW 433 | F       | 0.13                                     | 0.05                              | 0.0                             | 0.14        |
from a circumstellar disk. The Orion association is divided into four subgroups, labeled Ia, Ib, Ic, and Id. The subgroups are distributed roughly by age, with Ia being the oldest, Id the youngest, and an age difference of about 10 Myr. The Orion Nebula stars analyzed in this study are members of Id. The abundances in the two stars are $\mathcal{A}(C) = 8.40$ for JW 22, $\mathcal{A}(C) = 8.30$, and $\mathcal{A}(O) = 8.80$ for JW 433. For comparison, Cunha & Lambert (1994) studied three OB stars in Id, and their average (non-LTE) abundances are $\mathcal{A}(C) = 8.25$ and $\mathcal{A}(O) = 8.85$: the agreement between two K–M dwarfs and three OB stars is excellent. In addition, Cunha et al. (1998) have one F dwarf that is an Id member, and its oxygen abundance is $\mathcal{A}(O) = 8.86$: again, excellent agreement. Oxygen and carbon abundances in the OB stars come from analyses of O II and C II lines, while the oxygen abundance in the F dwarf comes from an analysis of O I lines. The K–M dwarfs use molecular OH and CO lines. This abundance comparison across a large range in $T_{\text{eff}}$ utilizing a variety of spectroscopic signatures provides evidence that the abundance analysis of the low-mass stars studied here is robust. We proceed to a discussion of the fluorine abundances.

Historically, $^{19}$F abundances were derived initially from a sample of galactic K, M, S, and C red giants, with metallicities mostly near solar, by Jorissen et al. (1992); this study was restricted to fairly bright stars in the IR. More recently, access to high spectral resolution in the IR using the Phoenix spectrograph on the Gemini South 8.1 m telescope has allowed fluorine abundances to be measured in fainter samples of cool stars, such as in the Large Magellanic Cloud (LMC) or in the globular cluster ω Centauri (Cunha et al. 2003). Renda et al. (2004) used the above-mentioned $^{19}$F abundances as comparisons to chemical evolution models. They conclude that both Wolf-Rayet and AGB stars are significant sources of $^{19}$F, with the Wolf-Rayet stars dominating at high metallicities. At low metallicities (less than roughly $-0.8$ dex), synthesis via the ν process in SNe II dominates fluorine production. Renda et al. (2004) were the first to show that all three $^{19}$F sources can be significant contributors, but with differing relative contributions depending on the metallicity and star formation history of the stellar population. In addition to abundances derived from stellar HF lines, Federman et al. (2005) have obtained detections of interstellar F I lines (at 955 Å) along two lines of sight into the Cep OB2 association using the Far Ultraviolet Spectroscopic Explorer (FUSE). Their derived column densities of F and O indicate a near-solar F/O ratio, with some small depletion effects.

The Orion stars analyzed here are of particular interest as they represent a different type of star with which to probe fluorine when compared to previous studies, since Jorissen et al. (1992) sampled only evolved stars. Our work adds three stars of higher when compared to previous studies, since Jorissen et al. (1992) represent a different type of star with which to probe fluorine and their $^{19}$F and $^{16}$O abundances are shown in Figure 3 in the surface gravity to the sample of near-solar metallicity field stars, sampled only evolved stars. Our work adds three stars of higher

values in Figure 3 are taken to be $\mathcal{A}(O) = 8.69$ and $\mathcal{A}(F) = 4.55$. Note that the Orion dwarf abundances overlap very nicely with the Jorissen et al. giants.

The stellar abundances that are plotted in Figure 3 represent all the available fluorine abundances that have been measured for members of the Milky Way so far (excluding self-polluted AGB stars). Abundances for LMC red giants from Cunha et al. (2003) are not shown here, as the star formation history and corresponding chemical evolution in the LMC may be quite different from the Milky Way. The solid curve in Figure 3 is a chemical evolution model from Renda et al. (2004) for the Milky Way. This particular curve represents their MWc model, which includes $^{19}$F yields from all three stellar production sites: SNe II with the ν-process, Wolf-Rayet stars, and AGB stars. The Orion Nebula Cluster F and O abundances help anchor the Milky Way values at high metallicity, which are fit nicely by the Renda et al. (2004) model with all three sources. The low values of [F/O] in the ω Cen stars were discussed by both Cunha et al. (2003) and Renda et al. (2004) in the context of the unusual star formation history and chemical evolution within this self-enriched stellar system that has been captured by the Galaxy.

6. CONCLUSIONS

We detect the HF molecular line at 23400 Å in K–M dwarfs and present the first fluorine abundance measurements in young stars still in the pre–main-sequence phase of evolution. These targets are members of the Orion association, in particular from the Orion Nebula Cluster, with masses around 0.4–0.8 $M_\odot$. Our results for JW 433 and JW 22, which do not show substantial emission from a circumstellar disk, reveal abundances of C and O that are in excellent agreement with those that are found in B-type stellar members of Orion Id (Cunha & Lambert 1994). This agreement bolsters confidence in the quantitative spectroscopic abundance analyses techniques used in the hotter B stars, as well as the cool K and M dwarfs. Moreover, JW 433 and JW 22 also display abundance patterns in agreement with the general behavior of fluorine versus oxygen for the Milky Way disk that has been established from stars in a distinctly different evolutionary state. All previous F abundances had been derived from studies of red giants. The overlap in these abundances provides an important...
confirmation for the relation of the fluorine abundance with oxygen in the disk.

In the future, larger samples of K and M dwarfs, as well as L and T dwarfs, can be used to measure fluorine and oxygen abundances both in the field and in the nearer star-forming regions.

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