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[Fe IV] IN THE ORION NEBULA[1]

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ABSTRACT

Using the Goddard High-Resolution Spectrograph on the *Hubble Space Telescope*, we measured the flux of [Fe IV] ($3d^5\ {}^4P_{5/2} \rightarrow 3d^5\ {}^6S_{5/2}$) $\lambda_{\rm vac} = 2836.56$ Å in the Orion Nebula, the first detection of an [Fe IV] line in an H II region. A useful upper limit is set on the sum of fluxes of [Fe IV] ($3d^5\ {}^4D_{5/2,\,3/2} \rightarrow 3d^5\ {}^6S_{5/2}$) $\lambda_{\rm vac} = 2568.4$, 2568.2 Å. By comparing these observations with predicted fluxes from simply "retrofitting" our two previous photoionization models, we are able to derive (or set an upper limit on) the Fe/H abundance ratio: 70, 200 times lower than solar from the 2837 Å line, and ≥38, ≥120 times lower than solar from the 2568 Å line limit. If collisional excitation from the ground state were indeed the dominant mechanism for populating the respective upper levels of these lines, then the inferred Fe/H from the 2837 Å line and limit from the 2568 Å line would be ~3.0 and ~3.4 times larger than above. All these ratios are much lower than several recent determinations of gas-phase Fe/H $\sim 3 \times 10^{-6}$ in Orion, which themselves are a factor ~10 depleted relative to solar. Because the inferred Fe/H should be at least as high in the Fe^{+3} zone as in the Fe^{+} and Fe^{+2} zones, a reexamination of the Fe^{+3} atomic data and improved modeling would be valuable.

Subject headings: H II regions — ISM: abundances — ISM: atoms — ISM: individual (Orion Nebula)

1. INTRODUCTION

Since the work of Zuckerman (1973) and Balick, Gammon, & Hjellming (1974), it has been realized that the overall spatio-kinematic picture presented by the Orion Nebula data is that of a "blister" configuration. The Trapezium stars and the ionized gas lie in the foreground of the molecular cloud OMC-1, all of which are viewed roughly face-on. Detailed photoionization modeling with such a blister geometry has been applied to Orion data in order to understand its structure and properties (Baldwin et al. 1991; Rubin et al. 1991a). From extensions of these papers, with particular emphasis on refractory elements in the Orion ionized region, the gas-phase iron abundance has been estimated (Rubin et al. 1991b, 1992; Rubin, Dufour, & Walter 1993; Erickson et al. 1996; Baldwin et al. 1996). There is good agreement among the model results with Fe/H ranging from 2.7 to 4.2×10^{-6} (by number). The models were computed independently using two separate photoionization codes (CLOUDY: Ferland 1996; NEBULA: Rubin et al. 1991a). Further support for a similar Fe/H value, 2.7×10^{-6}, came from Osterbrock, Tran, & Veilleux (1992).

In terms of the solar Fe/H (3.24×10^{-5}; e.g., Grevesse & Noels 1993), the above-range in nebular gas-phase abundance represents a depletion of 12–8. Depletions are routinely defined with respect to solar, although of course it is important to know whether the total (gas + dust) Fe/H is the same in the Orion Nebula as in the Sun. Van Steenberg & Shull (1988), using Fe II lines in *IUE* spectra along the line of sight to 12 stars in Ori OB1, found an average depletion for Fe of a factor 80, where we have adjusted to the Grevesse & Noels (1993) solar value.

Recently, it has been claimed that [O I] and [Fe II] lines are produced by a warm ($T_e \sim 10^4$ K) region with very high electron density ($N_e \sim 2 \times 10^6$ cm^{-3}) (e.g., Bautista, Peng, & Pradhan 1996 and references therein). Furthermore, they conclude that the gas-phase Fe/O abundance is about solar. Compared with the results from the above-mentioned studies of the ionized region, as well as diffuse interstellar medium line-of-sight absorption-line studies that show even higher depletions, such a high Fe abundance is most surprising and would have important implications for grain destruction mechanisms. On the other hand, Baldwin et al. (1996) found a good theoretical match to the [Fe II] lines—and to improved [O I] data that do not suffer from telluric emission—which is consistent with $\sim 10^4$ cm^{-3} gas and Fe/H $\sim 3 \times 10^{-6}$. This was done with only minor modifications to a previously proposed model of the Orion H II region (Baldwin et al. 1991).

Abundance analyses are most secure when lines from all pertinent stages of ionization of an element are observed. The analyses of the Orion ionized volume mentioned above make use of lines from Fe^{+} and/or Fe^{++} only, using models to assess the ionization fractions. For instance, Baldwin et al. (1991) predict $\mathrm{Fe}^{+}/\mathrm{Fe}^{++}/\mathrm{Fe}^{+3} = 0.0128/0.244/0.744$, while Rubin et al. (1991b) predict 0.0529/0.414/0.533, averaged over the entire nebula. Because Fe^{+3} is expected to be the dominant Fe species in Orion, the measurement of its lines would provide an important new handle on deriving the Fe abundance; this might be especially useful to help resolve the current controversy over the iron abundance in Orion. Unfortunately, Fe^{+3} does not have intrinsically bright lines under nebular conditions.

The main purpose of this Letter is to present our new *Hubble Space Telescope* (*HST*) observations of the features near 2837 Å. We interpret one of the components as the first

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detection of an [Fe IV] line in an H II region. This line ($3d^5\ {}^4P_{5/2} \rightarrow 3d^5\ {}^6S_{5/2}$) at $\lambda_{\rm vac}$ = 2836.56 Å (Fuhr, Martin, & Wiese 1988; Ekberg & Edlén 1978; the reader is referred to these papers for energy levels of Fe^{+3} that we discuss) has also been seen in RR Tel (Penston et al. 1983).

2. *HST* OBSERVATIONS

From our earlier Cycle 3 Faint Object Spectrograph (FOS) data, we combined spectra taken at three positions in the Orion Nebula in order to maximize the signal-to-noise ratio (S/N) for identification of faint lines in the UV (Rubin et al. 1995; see Fig. 1 [Pl. L14]). An emission feature at $\lambda_{\rm vac}$ = 2836.7 Å was thought to be a good candidate for emission from [Fe IV]. Subsequently, we were granted Cycle 5 time for deep, high-resolution spectroscopy of this wavelength region with the Goddard High-Resolution Spectrograph (GHRS).

We observed with the GHRS on 1995 October 14 (UT) using the large science aperture (LSA) with the G270M grating. The $1''.74$ square aperture was centered at α, δ = $05^{\rm h}35^{\rm m}14^{\rm s}.71$, $-05°23'41''.5$) (equinox J2000), $18''.5$ south and $26''.2$ west of θ^1 Ori C. These are the same coordinates used for our FOS Cycle 5 observations at position 1SW (although the size and shape of the apertures differ) (see Fig. 1). The grating was centered at 2816.52 Å in order to cover several lines of interest in the ~45.7 Å bandpass. The spectral resolution is ~0.1 Å for a point source (Fig. 8-1 in Soderblom et al. 1995). For a uniformly filled LSA, there are eight diodes illuminated, which is expected to cause a degradation in resolving power by a factor of 8. This is borne out by observations of geocoronal Lyα (see § 3 in Conti, Leitherer, & Vacca 1996). Hence, in the limit of a uniformly filled LSA, lines with FWHM ~ 0.8 Å could be expected. The exposure was 8486 s in ACCUMULATION mode. This is part of a larger study of the Orion Nebula with *HST* to be presented elsewhere; we limit our presentation of data here to that which is relevant to the matters at hand. As such, the long-wavelength portion of the spectrum is presented in Figure 2. We have applied a three-point boxcar smoothing to the calibrated spectrum.

With the enormous improvements that the GHRS spectrum provides in higher resolution and S/N, what had appeared as a single feature with FOS is now clearly three components. It is also immediately evident that the bulk of the emission in the FOS blend is not the [Fe IV] line at $\lambda_{\rm vac}$ = 2836.56 Å but the C II lines $2s^23p\ {}^2P^0_{3/2,\,1/2} \rightarrow 2s2p^2\ {}^2S_{1/2}$ at $\lambda_{\rm vac}$ = 2837.541 and 2838.439 Å (Huber, Sandeman, & Tozzi 1984). This multiplet (UV13) arises from 16.33 eV above the ground state and is thus of recombination origin.

Line fluxes were measured using the IRAF[10] ONEDSPEC: SPLOT software. We used both Gaussian-fitting deblend (*d*) and direct integration (*e*) routines to measure the net line flux above the continuum. Because the filled LSA introduced a spectral impurity into the spectrograph, the line profiles have flatter tops and less extended bases (e.g., are more "trapezoidal") than the Gaussian fits. The fit shown in Figure 2 is obtained by requiring that the known separation in $\lambda_{\rm vac}$ between the above three lines plus the He I 2829.91 Å line be maintained. There is only a single degree of freedom in the wavelength direction. Additionally, we force a single FWHM for all four lines since the width is set by instrumental resolution (here 62.7 km s^{-1} at 2836 Å line) and not the intrinsic width (i.e., the four are not expected to differ). Finally, the fit provides the best linear continuum baseline.

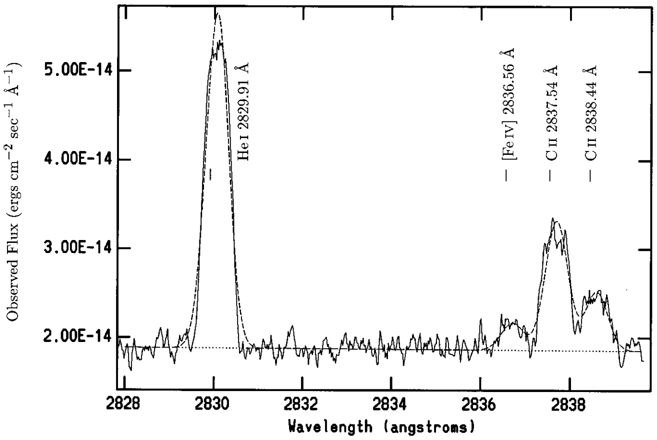

FIG. 2.—Portion of a GHRS spectrum of the Orion Nebula observed with the *HST*. This shows the four-component Gaussian fit (*dashed line*) to the four lines. The short vertical lines mark $\lambda_{\rm vac}$ for each labeled line. The flux here has not been adjusted for the 0.95 factor discussed in the text.

It is clear from the figure that the individual line profiles depart from the four Gaussians in the direction of the trapezoidal shape. We have also measured the line fluxes by the *e* routine; for the He I 2830 Å line, the flux is lower by 3.2% than the four-line *d* fit. It is apparent from the Gaussian fit of this line in Figure 2 that the flux is overestimated; hence, we use the lower value for this line. The measured line fluxes, representing integrated values over the LSA in ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, are presented in Table 1. We have multiplied the fluxes that result from the standard pipeline GHRS calibration (CALHRS) by 0.95 (recommended for a uniformly filled LSA; *HST* Data Handbook 1995, p. 377). This small correction is made because our measured line widths are closer to the uniformly filled LSA limit than to the point-source limit. The best-fitting FWHM for these four lines is 0.5937 Å with line center wavelengths 0.158 Å redward of the set of $\lambda_{\rm vac}$. This corresponds to $V_{\rm helio}$ = 16.7 km s^{-1}, in agreement with the ~17 ± 2 km s^{-1} from emission lines arising in the main ionization zone (O'Dell et al. 1993). Table 1 also has extinction-corrected fluxes. The corrections are based on our FOS data on Balmer, He I, and [O II] emission-line ratios at position 1SW, consistent with the shape of the extinction curve derived from observations of Orion stars (Martin et al. 1996). Errors (1 σ) are determined using a four-Gaussian nonlinear fitting program for the one-dimensional marginalized distributions of the amplitudes of the Gaussians, obtained from the quality of fit to the original unsmoothed data. These errors are statistical in the sense that they do not include systematic effects such as the instrumental calibration.

The identification of the two C II lines is very secure (see § 3). The observed $F(2837.5)/F(2838.4)$ is ~2, as expected from the statistical weights and similar A-values (Wiese, Fuhr, & Deters 1996 used for C II throughout this Letter). The identification of the third line as [Fe IV] is of course not as certain. A companion line from the multiplet ($3d^5\ {}^4P_{3/2} \rightarrow 3d^5\ {}^6S_{5/2}$) at $\lambda_{\rm vac}$ = 2830.22 Å is hopelessly lost in the much stronger He I 2829.91 Å line. The relative intensity of [Fe IV] 2830.22/2836.56 depends largely on collision strengths, which have been calculated recently (Berrington & Pelan 1995, 1997). We have applied their 12-level atom using typical N_e and T_e values from our models. For Orion, we expect

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[10] IRAF is distributed by NOAO, which is operated by AURA, under cooperative agreement with NSF.

TABLE 1

Observed and Extinction-Corrected Line Fluxes[a]

Source	[Fe IV] 2568.4, 2568.2[b]	He I 2829.91	[Fe IV] 2836.56	C II 2837.54	C II 2838.44
Orion 1SW............	0.61 ± 0.31	21.92 ± 0.34	1.84 ± 0.30	8.77 ± 0.31	3.98 ± 0.31
	3.23 ± 1.64	109.3 ± 1.70	9.19 ± 1.50	43.69 ± 1.54	19.85 ± 1.54

[a] Observed line flux and extinction-corrected flux (below) (10^{-15} ergs cm^{-2} s^{-1}). Errors are 1 σ and are statistical only.

[b] Line not detected. Measurement provided, but we use 3 σ as the upper limit.

$F(2830.22)/F(2836.56) \sim 0.5$–0.6; hence, the contribution to the He I 2829.91 Å line would be $\lesssim 5\%$. Even in the high-N_e limit, the observed flux ratio is expected to be close to the above—$F(2830.22)/F(2836.56) = (4 \times 0.89)/(6 \times 1.368) = 0.43$ (proportional to the products of statistical weights and transition probabilities from Ekberg & Edlén 1978). This is close to the observed line ratio of 0.46 (Penston et al. 1983) obtained from *IUE* for RR Tel, a slow nova (or symbiotic star) that should be in the high-N_e limit. They do not mention He I λ2829.91 as a possible identification, presumably because it is weaker judging from adjacent ($n = 5$ and 7) lines they do list in the He I sequence.

The only other [Fe IV] lines that Penston et al. measured (blended) in RR Tel are $^4D_{5/2,\,3/2} \rightarrow {}^6S_{5/2}$ ($\lambda_{\rm vac}$ = 2568.4, 2568.2 Å). Their expected flux ratio with our models is $F(2568.2)/F(2568.4) = 0.316$. In the high-$N_e$ limit, $F(2568.2)/F(2568.4) = (4 \times 0.028)/(6 \times 0.056) = 0.33$ (Ekberg & Edlén 1978). Penston et al.'s observed (combined) relative intensity is down by a factor ∼6 from the 2830.22 Å line. We also attempted to observe 2568.2 and 2568.4 in Orion with GHRS on 1995 October 14. The grating was centered at 2584.71 Å in order to cover several lines of interest in the ∼46.8 Å bandpass. The exposure was 4570 s. To extract the flux of [Fe IV] λ2568, we fitted the spectrum simultaneously with the nearest line Mn II λ2576.877 (in absorption), offset by the known difference in $\lambda_{\rm vac}$. The entry in Table 1 indicates a possible (2 σ) detection, but one must be cautious in interpreting the results because of potential systematic errors in the extraction technique.

While our identification of the 2836.56 Å line as [Fe IV] is based on just this one secure line, we have examined other possibilities and conclude that our basis is sound. We have checked for coincidences near this wavelength in the omnipresent Fe II line list. The closest is at 2838.13 Å (which would be blended with the red C II line). The O III Bowen fluorescence line at 2837.11 Å would also be clearly distinguishable by the disparity in wavelength with our observed feature. The fact that no O III fluorescence line is expected or observed in the Orion Nebula is also compelling.

3. OTHER LINES FROM THE C II MULTIPLET

In addition to the two C II lines near 2837, 2838 Å, the upper level gives rise to other C II lines that may be observable. We first discuss the multiplet (UV10) with $2s^23p\ ^2P^0_{3/2} \rightarrow 2s2p^2\ ^2D_{5/2}$ at $\lambda_{\rm vac}$ = 1760.40 Å and $2s^23p\ ^2P^0_{3/2,\,1/2} \rightarrow 2s2p^2\ ^2D_{3/2}$ at $\lambda_{\rm vac}$ = 1760.47 and 1760.82 Å (Huber et al. 1984). The intensity of each of these can be predicted from the intensities of the 2837.54 and 2838.44 Å lines and their A-values. Then $I(1760.40) = 1.563\ I(2837.54)$; $I(1760.47) = 0.1733\ I(2837.54)$; and $I(1760.82) = 1.738\ I(2838.44)$. We do not have GHRS observations of the 1760 Å region; however, we have FOS Cycle 5 spectra taken at the same position as our GHRS spectra, although the 0".86 diameter circular aperture is smaller. The FOS spectra were taken with gratings G190H, G270H, G400H, G570H, and G780H, which provide total coverage from ∼1650 to 7800 Å. Details of these FOS observations shall be reported elsewhere. The resolution of our FOS data is insufficient to resolve the C II multiplets at 2837, 38 or 1760, 61 Å.

To provide further assurance of the correctness of our identification of the C II lines, we prorate our measured 2837.5 and 2838.4 Å fluxes with LSA to that of the FOS aperture. This provides a sum for the flux in the two lines that is a factor 1.49 too small compared with the measured[11] sum using the G270H FOS grating. Because the LSA is not uniformly filled and we chose the FOS position to maximize potential flux, this is not surprising. Let us use the measured FOS flux and assume the sum is partitioned among the two C II lines in proportion to the GHRS values (we ignore the small [Fe IV] contribution in this exercise) to obtain 2.50×10^{-15} and 1.14×10^{-15} ergs cm^{-2} s^{-1}. Then the expected reddened fluxes are calculated for the 1760.40, 60.47, and 60.82 Å lines as 3.73×10^{-15}, 4.14×10^{-16}, and 1.89×10^{-15}, where a small differential extinction factor has been applied that is appropriate for position 1SW (Martin et al. 1996). The sum of these 1760 Å components is 6.03×10^{-15}, which compares fairly well with our measured FOS G190H flux 7.22×10^{-15}.

There is an unidentified feature blended on the blue side of our 1760 line at 1SW that has a difference in wavelength of ∼4.3 Å. Its flux is ∼60% of the 1760 Å flux. The wavelength of this feature is too high to be any of the five lines in the N III] multiplet (1746.8, 48.6, 49.7, 52.2, and 54.0 Å), especially when the 1749.7 component would be by far the strongest for Orion Nebula conditions, and is not seen. The unidentified feature appears to be present in the high-resolution *IUE* spectra of several sources, e.g., SWP 41903 of the planetary nebula IC 4997 (Fig. 3 in Keenan et al. 1994) and SWP 52689 of the symbiotic nova PU Vul (Fig. 6 in Nussbaumer & Vogel 1996).

We conclude that our tentative identification of our FOS Cycle 3 "combined spectrum" feature near 1760 Å is not N III] but is dominated by the C II lines. This brings the observed and vacuum wavelengths into good agreement (when we account for a systematic shift in the G190H grating). Another C II multiplet that originates from the same $3p\ ^2P^0$ upper level gives rise to $3p\ ^2P^0_{3/2,\,1/2} \rightarrow 3s\ ^2S_{1/2}$ at $\lambda_{\rm vac}$ = 6579.87 and 6584.70 Å. It can be shown that the ratio of the sum of fluxes for these C II lines to the [N II] ($\lambda_{\rm vac}$ = 6585.23 Å) line flux (with which they are blended in our FOS/G570H data) is 0.003—negligible here.

4. DISCUSSION AND CONCLUSIONS

With the measurement of [Fe IV] 2836.56, we have a new tool to address gas-phase Fe/H in the Orion Nebula – for the first time from the dominant Fe stage of ionization. The effective collision strengths from the ground state (Berrington & Pelan 1995) are partitioned assuming *ls* coupling and T_e =

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[11] To obtain measured flux with the FOS, we have applied a correction factor for extended sources to the pipeline calibrated spectrum (see *HST* Data Handbook 1995, pp. 286–287).

10^4 K. For the range of expected T_e in Orion, there is little variation of these effective collision strengths. For values between levels 2–12, we use corrected numbers in their Erratum (Berrington & Pelan 1997).

Two independent, previously proposed Orion models (of different regions) are applied to make predictions of the flux expected for [Fe IV] 2836.56: CLOUDY (Baldwin et al. 1991) and NEBULA (Rubin et al. 1991a, 1991b). Each model is calculated with a nominal Fe/H $= 3.0 \times 10^{-6}$. A linear scaling of the predicted iron line intensities with Fe/H is valid because iron line cooling is negligible. We are interested in deriving Fe/H from [Fe IV] and choose to use Hβ as the indicator for hydrogen. Because we have no GHRS H-line data, we utilize our Cycle 5 FOS data at position 1SW (see § 3 and Fig. 1).

Our measured flux with FOS/G270H for He I 2830 is 5.95×10^{-15} ergs cm^{-2} s^{-1}, where deblending from the C II redward lines has been done. Our measured Hβ flux (FOS/G570H) is 6.92×10^{-13}. Assuming that this observed $F(2830)/F(\mathrm{H}\beta)$ applies to the larger area of the GHRS/LSA (centered at 1SW), and using the measured GHRS ratio from Table 1, we find $F(2837)/F(\mathrm{H}\beta) = 7.23 \times 10^{-4}$. This flux ratio, corrected for differential extinction at 1SW, becomes 9.55×10^{-4}. The predicted (intrinsic) flux ratio is 2080 Fe/H using NEBULA and a factor 2.88 larger using CLOUDY. This difference for the most part is due to the higher T_e in the latter model (on average, ~9100 vs. ~8000 K). The fractional ionizations Fe^{+3} in the column defined by the beam are similar in both models and predict that Fe^{+3} is the dominant iron ion. By comparing the model predictions with the observed extinction-corrected ratio, we conclude that Fe/H $= 4.6 \times 10^{-7}$ with NEBULA and 1.6×10^{-7} with CLOUDY.

For similar analysis of the [Fe IV] 2568 Å line, we take as the flux upper limit 9.3×10^{-16} (3 σ; see Table 1). Thus, $F_{\mathrm{corr}}(2568.4 + 2568.2)/F_{\mathrm{corr}}(\mathrm{H}\beta) \leq 5.10 \times 10^{-4}$. We compare our model predictions for the sum of the 2568.4 and 2568.2 Å fluxes relative to the Hβ flux (594 Fe/H using NEBULA and 1840 Fe/H using CLOUDY) with the extinction-corrected flux limit. This provides an upper limit on Fe/H of 8.6×10^{-7} with NEBULA and 2.8×10^{-7} with CLOUDY. Further detailed modeling, keying on the region in question, is underway. Our work here illustrates the large uncertainty rendered by sensitivity to T_e. This shows the difficulty of obtaining abundances from UV lines under these circumstances. It points to advantages of using IR lines to minimize T_e (and extinction) uncertainties and of using ratios of lines that are close in wavelength and excitation levels.

We note some strange consequences as a result of using the Berrington & Pelan (1995, 1997) collision strengths. The most important routes to populating $^4P_{5/2}$ are spontaneous emission from the ^4D term, collisional excitation from the ^4G levels, and, a poor third, collisional excitation from the ground state. The most important route to populating $^4D_{5/2,\,3/2}$ is by far collisional excitation from the ^4G levels and not from the ground state. Spontaneous emission between all 12 levels is treated with A-values from Garstang (1958) unless given by Ekberg & Edlén (1978). We can force the dominant excitation route into the upper levels of the [Fe IV] lines measured to be collisional excitation from the ground by treating only collisional excitation and deexcitation involving the ground state (setting to zero the collision strengths between levels 2–12). The net change for Orion is to decrease the $^4P_{5/2}$ population a factor ~3.0 and the $^4D_{5/2,\,3/2}$ populations a factor ~3.4, resulting in corresponding *increases* in the Fe/H ratios inferred. A comment also regarding A-values, in particular for the ^4G levels, is that low A-values allow these to act as trapping levels, with the population distributed nearly proportional to the statistical weights at very low N_e. A critical reevaluation of the A-values also would be valuable.

Taken at face value, our results are much lower than several recent determinations, from other ionization stages, of gas-phase Fe/H ~ 3×10^{-6} (about an order of magnitude depletion). If the total (gas + grains) Fe/H in the Orion Nebula is solar, the bulk of Fe is still locked in grains, even in the harsh environment of the Fe^{+3} zone. The work of Cunha & Lambert (1994) may be drawn upon to assess whether the *total* Fe/H differs in Orion from the Sun. Their analysis of nine Fe III lines in main-sequence B stars in the Orion association (see their Fig. 12) may be used to gauge possible departures. If we interpret a departure in the average level of their data points for a given Fe III line as a correction needed to the Orion Fe/H ratio, we find for the most extreme cases that Fe/H would have to be roughly 1.6 times higher and 2.0 times lower than solar. Their fits, as a whole, show no clear evidence for a stellar Fe/H ratio that differs from solar.

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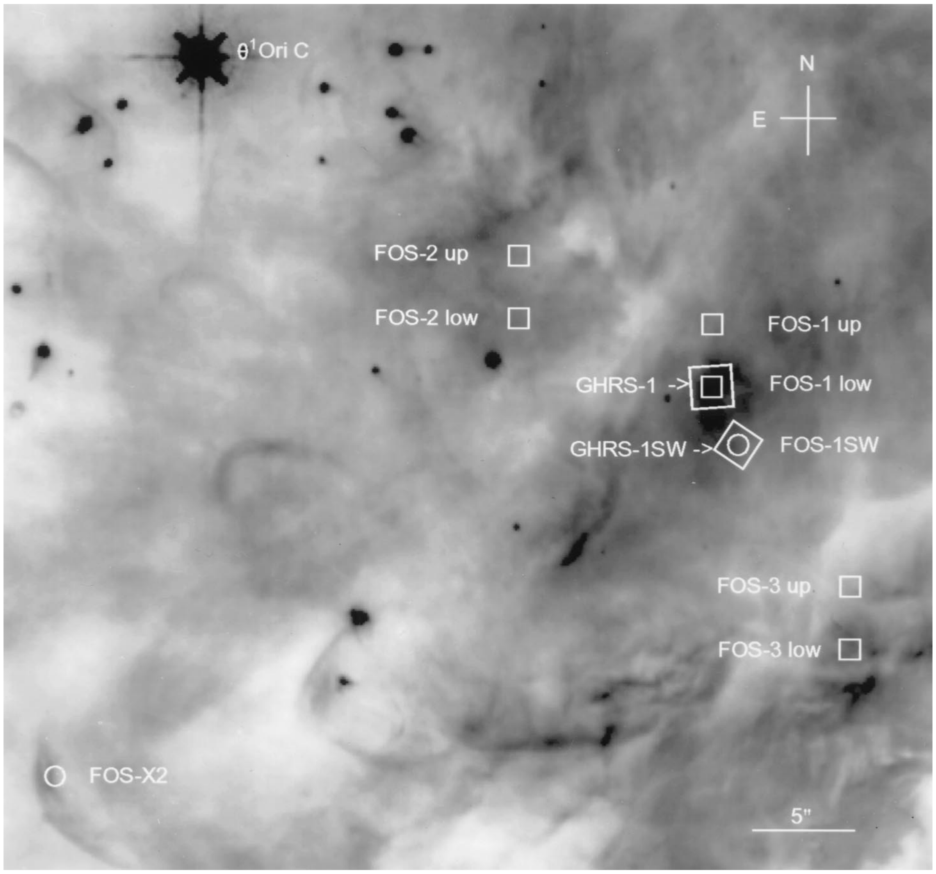

FIG. 1.—WFPC2 Hα image (from C. R. O'Dell's collection) of the Orion Nebula showing the locations of our GHRS and FOS observations in Cycles 5 and 3. (Not all positions are referred to here but are needed for other papers in this series). The GHRS Cycle 5 data discussed (see Fig. 2) were taken through the LSA (1$''\!.$74 square) aperture GHRS-1SW. The FOS Cycle 3 combined spectrum (§ 2) is the sum of 1 low, 2 low, and 3 low. The location of θ^1 Ori C is indicated. The horizontal bar in the lower corner is 5$''$ long.

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