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HST FOS SPECTROSCOPY OF THE DUSTY SMC H II REGION N88A[1]

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RESUMEN

Entre las regiones H II de la Nube Menor de Magallanes, N88A es una pequeña nebulosa de especial interés porque tiene una cantidad importante de polvo asociado a ella. Presentamos y discutimos imágenes tomadas con la cámara planetaria del *Telescopio Espacial Hubble HST* en 1993. Tambien obtuvimos espectros con el espectrógrafo *HST*–FOS que muestran un espectro rico en líneas en emisión. La intensidad de estas líneas permite determinar con precisión las condiciones físicas y las abundancias de C, N y O en N88A. Encontramos que O/H es similar mientras que C/H y N/H son marginalmente mayores a los valores encontrados en otras regiones H II de la Nube Menor de Magallanes. Damos argumentos en favor de que probablemente una fracción importante del polvo en la dirección de N88A pertenezca a la nube molecular que dio origen a las estrellas en N88A.

ABSTRACT

Among the H II regions of the SMC, N88A is a small nebula of special interest because there are large amounts of dust associated with it. We present and discuss *HST* WFPC1 images taken in 1993. *HST*–FOS spectra were also taken that reveal a rich emission line spectrum in the UV. The emission line strengths enabled accurate derivation of physical conditions and CNO abundances in N88A. When compared with abundances of other SMC H II regions, the O/H value derived for N88A is similar, while C and N are marginally higher. We argue that probably most of the dust located between N88A and the observer belongs to the molecular cloud that gave birth to N88A and that is in the process of disruption.

Key words: **H II REGIONS — DUST, EXTINCTION — GALAXIES: INDIVIDUAL: SMALL MAGELLANIC CLOUD — STARS: MASS-LOSS**

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1. INTRODUCTION

N88A (also called DEM161 from the catalog of Davies, Elliot, & Meaburn 1976) is a small (FWHM = 2.4″ in Hα) emission knot in the H II complex N88 (Henize 1956) located in the Shapley Wing of the Small Magellanic Cloud (SMC). Being one of the brightest outlying emission regions, Dufour & Harlow (1977) selected N88A for spectroscopic observation in a study of ten SMC H II regions, and found it to have an unusually large logarithmic extinction at Hβ, c(Hβ)$\sim$ 0.6, compared to all of the others, c(Hβ) $\leq$ 0.1. Subsequently, Testor & Pakull (1985) made a detailed study of its morphology, spectrum, and association with nearby stars. They noted that both the extinction and excitation peaked near the center of the nebula, indicating that it contained large amounts of internal dust. Koornneef & Israel (1986) found N88 to have a strong IR continuum and emission from shocked H_2 from ground-based and *IRAS* observations. Roche, Aitken, & Smith (1987) studied 8–13 μm spectra of N88A and found a featureless continuum, suggesting that the dust is likely composed of carbon grains. Molecular CO has been detected in N88 in the SMC survey of Rubio et al. (1993). Recently, Wilcots (1994a,b) presented radio-continuum and optical images, and spectroscopy of N88A, as well as UBV photometry of its associated star cluster. He noted that the most luminous star located near the nebula "core" was of spectral type O9V.

Since the dust-to-gas ratio in the ISM of the SMC is about a factor of ten lower than in the solar neighborhood (Martin, Maurice, & Lequeux 1989), N88A is an interesting situation of a very metal-poor H II region containing dust. In order to study the nature and possible origin of the dust, as well as the properties of the ionized medium and associated stars in N88, we were granted *HST* time to take FOS UV-optical spectra and WFPC1 imagery of the nebula. This contribution reports on the initial results of some of the observations.

2. OBSERVATIONS

Spectra were taken with the FOS during 1993 October using the G130H, G190H, G270H, G400H, and G570H gratings, which resulted in complete spectral coverage from 1150–6800 Å. Three sets of spectra were taken: one set with the 0.7 × 2.0″ "Bar" aperture which occulted the center of the nebula, and another set with a pair of 1.0″ square apertures, with one centered on the nebula and the other located 3.0″ off-center (towards PA = 190°). The effective spectral resolution (FWHM) was $\sim$ 4 Å near C III] λ1909 and $\sim$ 8.5 Å near Hα for the Bar spectra and about 4 Å and 10 Å, respectively, for the Square spectra.

WFPC1 images were taken in 1993 July using the F336W, F439W, F502N, F555W, and F656N filters, which respectively imaged the nebula in the U, B, [O III] λ5007, V, and Hα bands. All of the images were split exposures for rejection of cosmic rays in the reductions. Note that these images were *pre*-COSTAR, so we applied the STSDAS Lucy-Richardson deconvolution scheme with theoretical PSFs appropriate for the filters in order to improve the effective resolution. The processing of the FOS Bar spectra and the WFPC1 images were done using the calibrations available in late 1993. However, the Square aperture spectra were reprocessed in late 1994 with new calibration data appropriate for the 1.0-PAIR apertures.

3. IMAGERY RESULTS

In Figure 1 we present two of our deconvolved images of N88A: an Hα surface brightness image on the left and a grey-scale Hα minus [O III] difference image on the right. Note that on the Hα image, the nebula is basically bipolar shaped, apparently due to a dust lane running through the center, with a semi-stellar object seen towards the lower (western) side of the image. This side also has the higher surface brightness of the two lobes, particularly in [O III]. In the difference image, the level of white designates relatively more Hα along the line of sight, so relatively stronger [O III] emitting regions would appear dark. Note that the off-center star appears dark, due to enhanced [O III] emission surrounding it, and an arc of [O III] emission appears to join it to another semi-stellar object located near the geometrical center of the nebula. This central "star", which is faintly seen on the UBV images, may be the primary ionization source that is heavily obscured by the lane of dust running across the center of the nebula. The O9V star reported by Wilcots (1994a) is the lower (western) star; he apparently did not detect the central semi-stellar object. The exact nature of the [O III] arc is unclear, but possibly due to stellar winds or mass loss from one or both of the two stars.

4. SPECTROSCOPY RESULTS

Table 1 gives a selected set of measured UV-optical emission line strengths for the Bar and centered Square spectra. Line fluxes were determined from Gaussian line profile fits. For heavily blended multiplets the area

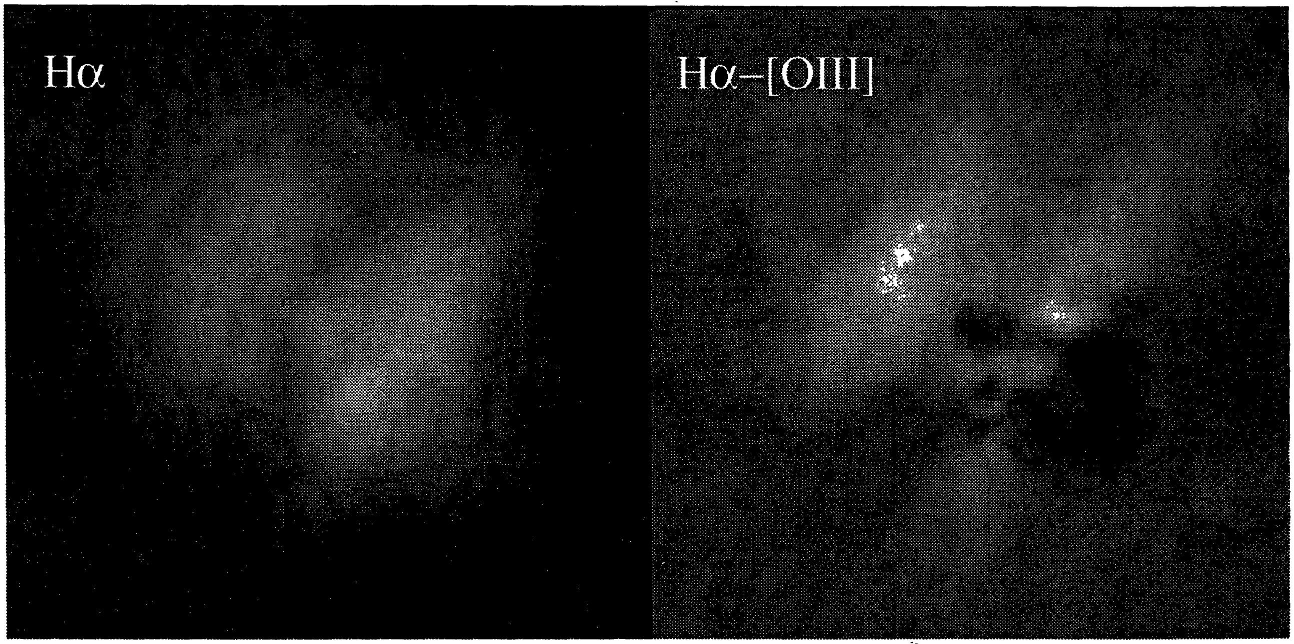

Fig. 1. Grey scale WFPC1 images of the Hα surface brightness (*left*) and the difference image of Hα-[O III] for SMC N88A (*right*). Both images were processed to restore the *HST* resolution to $\sim 0.2''$. The diameter of each field is $10.0''$ (equal to 3.4 pc at the distance of the SMC) and the direction of North is towards the top-right (44° clockwise from vertical). Note the dark curved arc joining two semi-stellar objects on the difference image.

under the combined line profile was used. Errors were determined by multiplying the FWHM of the line by the rms continuum noise, and are presented as 1σ *statistical* errors in the table. We note that, in addition to the statistical errors of a given line/multiplet measurement, systematic errors amounting to 5–15% may be present for a given line, or for line ratios which span a large wavelength range (>100 Å). This systematic error is due to the combination of the of the FOS calibration and the poorer photometric accuracy of FOS involving extended source observations through the larger apertures which overfill the reticon detector (Bohlin 1994).

We derived the logarithmic extinction at Hβ, c(Hβ), defined by

$$\log \mathrm{I}(\lambda)/\mathrm{I}(\mathrm{H}\beta) = \log \mathrm{F}(\lambda)/\mathrm{F}(\mathrm{H}\beta) + \mathrm{c}(\mathrm{H}\beta)\mathrm{f}(\lambda),$$

where F(λ) is the observed line flux, I(λ) is the line intensity corrected for interstellar reddening, and f(λ) is a function which describes the dependence of extinction on wavelength. We compared the theoretical ($\lambda\lambda$1660+1666)/(λ5007) ratio for [O III] with the observed ratio in each of the two spectra assuming an SMC reddening law (Prévot et al. 1984) for the UV ($\lambda \leq 3000$ Å) and the Seaton (1979) law for optical lines. For each of the two spectra, T_e was derived from the ($\lambda\lambda$4959+5007)/(λ4363) ratio, adjusted for reddening and possible FOS calibration errors, by assuming that the ratio of Hγ/Hβ = 0.471 (Brocklehurst 1971; appropriate for $T_e = 15\,000$ K and $N_e = 10\,000$ cm^{-3}). N_e values were derived from the ratios Si III] (λ1883)/(λ1892) and [S II] (λ6717)/(λ6730). The results and estimated errors are given at the bottom of Table 1. The program used in these calculations, as well as those which follow, is similar to the ***nebular.stsdas*** 5-level atom code described by Shaw & Dufour (1995), which gives references to the atomic data used.

The use of the UV–optical lines of [O III] for determining the extinction was necessary because of unanticipated inconsistencies in the c(Hβ) values derived from various H I and He I lines based on any reasonable extinction curve. These discrepancies are probably due to the FOS apertures overfilling parts of the reticon, producing a wavelength dependent error in the instrumental sensitivity from that derived from point sources. Since we have an accurate T_e for [O III] and the $\lambda\lambda$1660–5007 baseline spans most of our wavelength range, the use of this ratio seemed to be the most valid method possible at present.

TABLE 1

SMC N88A LINE INTENSITIES

		Bar			Square		
λ (Å)	Ion	10^{15}F	1σ	I(λ)/I(Hβ)	10^{15}F	1σ	I(λ)/I(Hβ)
1663	[O III]	26.2	2.8	21.7	64.3	4.1	18.9
1750	N III]	3.2	3.2	2.4	9.3	13.0	2.5
1883	Si III]	12.4	0.7	8.0	39.3	4.7	8.9
1892	Si III]	10.1	0.7	6.4	34.8	4.5	7.9
1909	C III]	108.	0.9	68.3	323.	3.4	72.6
2325	C II]	12.8	1.8	5.6	41.6	4.6	6.5
2470	[O II]	7.0	0.6	2.9	20.4	2.4	3.0
3727	[O II]	115.	1.9	29.6	286.	3.9	26.0
4340	Hγ	185.	0.9	43.8	478.	2.2	40.2
4363	[O III]	48.0	0.8	11.4	115.	2.2	9.7
4861	Hβ	456.	1.1	100.0	1287.	5.3	100.0
4959	[O III]	1229.	3.0	266.	3353.	8.8	257.
5007	[O III]	3623.	1.4	778.	10040.	10.0	781.
6563	Hα	1755.	2.1	315.	4791.	7.8	305.
6583	[N II]	30.0	1.9	5.4	74.0	10.0	4.7
6717	[S II]	9.0	2.4	1.6	20.0	16.0	1.3
6730	[S II]	16.0	2.8	2.8	26.1	16.0	1.6

		Bar	Square
T_e	[O III]	13 500±500	13 100±600
N_e	[Si III]	7 700±3 500	10 700±8 000
N_e	[S II]	5 400±3 500	1 670±?
N_e	average	6 500	6 200
c(Hβ)		0.27	0.27

5. ABUNDANCES

Our deep, high-resolution UV-optical FOS spectra permitted measurement of the UV intercombination lines of N III], C III] and C II], which along with the strong collisionally excited lines of [O II], [O III], and [N II], enabled the ionic abundances of C^+, C^{+2}, N^+, N^{+2}, O^+, and O^{+2} to be derived directly from observed lines. We used the reddening corrected line strengths in Table 1 and the theoretical line emissivities from the 5-level program calculated assuming T_e = 13 500 K and N_e = 6500 cm^{-3} for the Bar region and T_e = 13 100 K and N_e = 6200 cm^{-3} for the Square region. The adopted densities were the average of the values derived from the Si III] and [S II] nebular ratios. For the case of the Square spectrum, where the [S II] lines indicated a much lower density than from Si III], the [S II] lines were badly blended and our ratio determination from a combined profile fit of two Gaussian profiles is very uncertain.

Space considerations preclude us from presenting detailed ionic abundances derived from the two spectra. However, we note that similar ionic abundances relative to H^+ for the various ions were obtained for both positions. Because no He II lines, which are of rather high excitation for an H II region, are seen in any of the spectra we expect that most of the CNO will be in the 2nd ionization state. This is evident by the fact that $N(O^{+2})/N(O^+) \approx 16$ for both positions (unusually high for a H II region). Therefore, to get the total elemental abundances of C, N, and O, we summed the ionic abundance of the 1st and 2nd ionization states: $C \equiv C^+ + C^{+2}$, $N \equiv N^+ + N^{+2}$, and $O \equiv O^+ + O^{+2}$. The computed elemental abundance results and estimated 1σ errors are given in Table 2. The small errors for the C and O abundances reflect our accurate T_e determinations and the strong C III] and [O III] measured, while the larger errors for N reflect the errors in measuring the broad and weak N III] multiplet.

6. DISCUSSION

The CNO abundances calculated for the two sets of spectra of N88A are in relatively good agreement: the O/H values are essentially identical, and both C/H & N/H agree to ±0.11 dex. We note that the C/H and

N/H results depend strongly on the UV line ratios of C III] $\lambda\lambda$1907+9 and N III] $\lambda\lambda$1747–54 to Hβ, which are strongly influenced by the adopted extinction corrections. The magnitude of the extinction was found to be identical for the two spectra, and the values are based on the *assumption* that the SMC law is most appropriate. Use of the LMC or galactic extinction laws would result in a higher c(Hβ) more similar to that obtained from ground-based spectrophotometry. The identical c(Hβ)'s are also surprising based on where we think the FOS apertures were placed, given Testor & Pakull's (1985) result that the nebula is very centrally peaked in ionization and extinction. But the reddened line strengths of the two spectra are very similar when they are scaled to the same Hβ flux and overplotted. Unfortunately, we were not able to obtain a WFPC1 Hβ image of N88A which would have enabled us to map the spatial variation in the extinction (and ionization) across the nebula.

TABLE 2
SMC N88A ABUNDANCES[a]

Position/Study	12+[O/H]	12+[N/H]	12+[C/H]	[N/O]	[C/O]
SMC N88A Bar	8.09±0.08	6.60±0.34	7.40±0.10	-1.49±0.34	-0.69±0.12
SMC N88A Square	8.11±0.08	6.68±0.48	7.51±0.12	-1.43±0.48	-0.60±0.14
SMC (Dufour 1984)	8.02±0.08	6.46±0.12	7.16±0.04	-1.56±0.14	-0.86±0.06
N88A (Garnett et al. 1995)	8.09±0.04	–	7.37±0.15	–	-0.72±0.17

[a] [X/Y] = log$N$(X)/N(Y)

At the bottom of Table 2 we compare the CNO abundances of SMC N88A with the average for H II regions in the SMC from *IUE* and ground-based studies, as given in the review by Dufour (1984), and a more recent *HST* FOS study of C/O in several extragalactic H II regions by Garnett et al. (1995), which utilized the N88A Bar spectrum. Garnett et al. derived the C/O value from the UV O III]/C III] (λ1666)/($\lambda\lambda$1907+9) ratio directly using the low density limit formula:

$$\mathrm{N(C^{+2})/N(O^{+2}) = 0.089\ e^{-1.09/t}\ I(\lambda\lambda 1907 + 9)/I(\lambda 1666)},$$

where $t = T_e/10^4$, and used models to determine the ionization correction factor. Our calculation of C/O for the Bar spectrum, which is based on both C^+ and C^{+2}, gives a similar result. The C/O values so derived are higher by ~0.2 dex than those listed for the SMC ISM in Dufour (1984), which are based on *IUE* observations for C III]. Even when newer atomic data for C III] since 1984 are taken into account, the difference is still sufficient to lead us to conclude that N88A may be slightly C-rich. Our N/O result, which is largely based on a weak broad N III] $\lambda\lambda$1747-54 multiplet, is also slightly higher than the SMC average from Dufour (1984). However, the average SMC N/H value is based on ground-based spectra of the [N II] red lines near Hα, which are weak and the ionization correction factors for N^+ are very large. Here we present the first results in the literature of N abundances derived from the UV N III] lines for a metal-poor extragalactic H II region.

The dust-to-ionized-gas ratio in the direction of N88A is very high and considerably higher than in the direction of other SMC H II regions. There are two possible explanations for this result: (1) that mass loss from one or more massive stars in N88A is responsible for the dust formation or (2) that most of the dust is associated with the molecular cloud that gave birth to the massive stars in N88A (part of the molecular cloud would have to be located between N88A and us). In favor of the second possibility we have the following arguments: (a) the electron density is very high, which indicates that we are dealing with a very young H II region; (b) a CO cloud has been detected in the direction of N88A with a radius of 6 pc (Rubio et al. 1993; Lequeux et al. 1994), moreover the large differences in width between the ^{13}CO and the ^{12}CO lines for N88A as well as the high ^{13}CO(2–1)/^{13}CO(1–0) value indicate that the UV radiation field of N88A is very close to the molecular cloud (Lequeux et al. 1994); and (c) the O/H value indicates that there has not been substantial O enrichment of the gaseous component due to mass loss from massive stars in N88A (alternatively, the N and C values are marginally higher but still within the errors of the values derived from other SMC H II regions). Only the imaging results show evidence for any winds or mass loss appropriate to the first possibility; but all of the other evidence indicate that such phenomena, if they exist, have not significantly affected the abundances or physical state of the ionized gas in N88A.

In the future we plan an evaluation of the wavelength dependence of the extinction in N88A, based on comparison of the UV continuum of N88A and other SMC H II regions of low dust content using *IUE* archival spectra. In addition, we are analyzing long-slit CCD spectra of N88A taken with the CTIO 4-m telescope to evaluate the spatial variations in various physical properties across N88A. Once the results of these data become available, and the extinction with wavelength and position is clarified, we hope to be able to model the nebular structure from the images and the physical state of the ionized gas from the spectra in more detail using a nebular photoionization code.

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