ULTRAVIOLET IMAGING TELESCOPE OBSERVATIONS OF OB STARS IN THE N 11 REGION OF THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present an analysis of far-ultraviolet (FUV; 1300–1800 Å) and optical (U, B, and V) data of the stellar and nebular content of the OB associations LH 9, 10, and 13 in the Large Magellanic Cloud region N 11. The FUV images from the Ultraviolet Imaging Telescope strongly select the hot O and B stars; over 1900 stars were detected in the FUV to a limiting magnitude of $m_{152} = 17$ mag. The resulting FUV photometry combined with optical ground-based data indicate there are approximately 88 confirmed or candidate O stars in the LH 9, 10, and 13 fields alone (in an area of ∼41 arcmin^2) and possibly as many as 170–240 O-type stars within the entire 40′ diameter field of view.

Subject headings: Magellanic Clouds — open clusters and associations: individual: N 11 — stars: early-type — ultraviolet: stars

1. INTRODUCTION

N 11 (Henize 1956) is a spectacular star formation region in the Large Magellanic Cloud (LMC), at the center of N 11 is the OB association Lucke-Hodge 9 (LH 9; Lucke & Hodge 1970), and in the north is LH 10, which is extremely rich in early-type O stars (Parker et al. 1992). Other OB associations in the N 11 region are LH 13 to the east and LH 14 to the northeast. The entire region is buried in extensive and complex nebulosity. Although it resides in the distant northwest outskirts of the LMC, the N 11 region is the second largest H II region in the Magellanic Clouds according to the Hα flux measurements of Kennicutt & Hodge (1986); only the starburst region 30 Doradus has a larger Hα luminosity. Other morphological and evolutionary similarities between N 11 and 30 Dor have been discussed by Walborn & Parker (1992), indicating that N 11 is a more evolved (by about 2 Myr) version of 30 Dor. Analogous to R 136 in 30 Dor, the dense star cluster HD 32228 at the core of LH 9 contains a W-R star of type WC 5-6 and evolved O stars.

It is likely that sequential star formation has occurred in N 11 (Parker et al. 1992; Rosado et al. 1995), with stellar evolution in LH 9 triggering formation in the surrounding regions including LH 10. LH 9 resides in what appears to be a supernova-evacuated and/or wind-blown bubble and contains no stars earlier than O6, whereas LH 10 is within a region of strong and highly variable nebulosity and is rich in very early O stars having at least three and possibly as many as six O3 stars, as well as half a dozen "ZAMS O stars" (Parker et al. 1992). However, these ground-based studies have not covered the entire area of the N 11 region, and it is possible that many O stars remain undetected. This is particularly true for the perimeter of the nebulosity surrounding LH 9; there have been studies of LH 10 to the north, but none of the other regions around LH 9. The observations made by Ultraviolet Imaging Telescope (UIT) provide ideal data for a complete analysis of the massive star population and evolutionary history of the N 11 region.

UIT's UV capabilities and wide field (40′ diameter) with moderate spatial resolution (∼3″) are extremely well suited for massive star studies in the Magellanic Clouds. The Clouds are close enough that individual stars can be resolved, and in the ultraviolet, cool companions of hot stars are strongly selected against, so binaries are less of a concern. Magellanic Cloud OB associations tend to be a few arcminutes in diameter, so in a single image UIT can obtain UV photometry of cluster members (usually more than one cluster per image) and background field stars. This is a great improvement over the smaller CCDs that sometimes must be mosaiced to obtain data on a single cluster. Also, optical photometry is not well suited for determining temperatures (and therefore, masses) of the hottest, most massive OB stars, so that follow-up spectroscopy must be obtained to classify stars before a cluster's initial mass function (IMF) or ionizing flux can be determined. On the other hand, UV photometry can more accurately determine the temperatures of the hottest stars than can visible photometry and also provides data on thousands of stars in the time it takes to get a classification spectrum of a single star.

In this Letter we report first results of the UIT observations of N 11 and discuss improved insights these data provide into the stellar content of this spectacular star-formation region.

2. DATA

During the Spacelab Astro-2 mission which flew aboard the space shuttle *Endeavour* on 1995 March 2–18, UIT obtained more than 700 far-ultraviolet (FUV) images of nearly 200 celestial targets. The images include 16 fields in LMC and three fields in the SMC (Parker et al. 1996a). The UIT observations of N 11 made on 1995 March 13 consist of three exposures
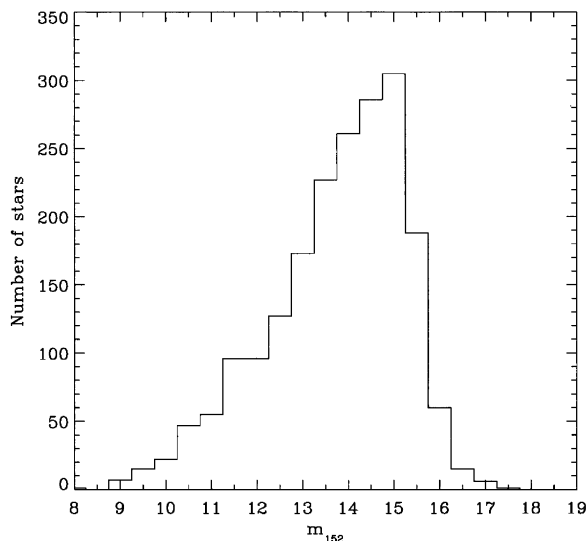
FIG. 2.—Observed m_{152} magnitude histogram of the all the stars detected by UIT in the N 11 region.

FIG. 3.—Observed CMD for LH 9 (*filled circles*), LH 10 (*open circles*), and LH 13 (*crosses*). Boxes connected by a line show the intrinsic main-sequence positions using data from the Fanelli et al. (1992) UV library, assuming a distance modulus to the LMC of 18.5; the triangles show the location of supergiants. The dotted line shows the reddening line for a O9 star assuming the 30 Doradus reddening law, and the dashed line is for the LMC (non-30 Doradus) reddening law using the reddening laws from Fitzpatrick (1985). The error bars shown for one of the data points indicate a 0.15 mag error in the UV magnitude and a 0.05 mag error in the V magnitude.

(39 s, 197 s, 986 s) in the B1 filter, which has a centroid wavelength of $\lambda = 1521$ Å, and a bandwidth of $\Delta\lambda = 354$ Å (see Stecher et al. 1992 for the filter response curve). The 40' diameter photographic images were scanned and digitized with a PDS 1010m microdensitometer, resulting in images with 1".13 pixels and point-source profiles with FWHM = 3".36 ± 0".29. Calibrations were made in the same manner as for Astro-1 (Stecher et al. 1992), based on laboratory measurements and data obtained during the missions. Flux value zero points were derived primarily with comparisons to *International Ultraviolet Explorer* (*IUE*) stars, but also with comparisons to stars observed by OAO-2, HUT, ANS, GHRS, and other UV instruments (Stecher et al. 1992). UV magnitudes are defined from these fluxes as: $m = -2.5 \log (F_\lambda) - 21.1$. Astrometry was performed with reference to *HST* guide stars (Lasker et al. 1990). A UIT image of the N 11 region is shown in Figure 1; Plate L5.

Stellar photometry on the images was performed with IDL procedures based on the DAOPHOT algorithms (Stetson 1987). Aperture corrections were calculated for each image, and small corrections were made in the zero-point offsets so that the median difference of the flux for all stars was zero between the three images (putting all three images on the same zero point). The final magnitude for each star is the average of its measurements on the three images weighted by the inverse square of its calculated photometric errors. A comparison with *IUE* observations of three relatively uncrowded stars in the field show that the UIT and *IUE* fluxes agree to better than 5%.

Figure 2 shows the histogram of observed FUV magnitudes. The limiting magnitude is $m_{152} \approx 17$ mag, the magnitude of an unreddened late B-type (~B9) star. The completeness limit, the magnitude to which we should have detected all stars, is $m_{152} \approx 15$ mag, the magnitude of an unreddened early B-type (~B3) star. The completeness limit of the ground-based data of Parker et al. (1992) goes to slightly later spectral types, so the combined UIT and ground-based data set is limited by the FUV data.

The ground-based data are from Parker et al. (1992), roughly 5' × 3' fields for each of the LH 9 and LH 10 regions, and from DeGioia-Eastwood, Meyers, & Jones (1993), cover-

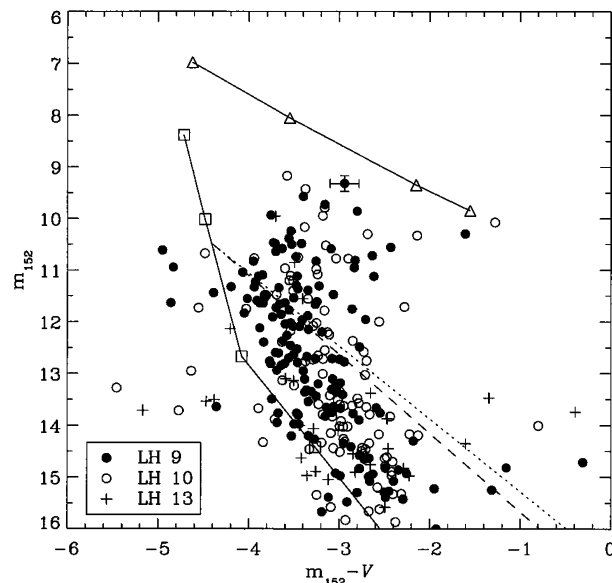ing a 4'.1 × 2'.6 region of LH 13. Outlines of the ground-based fields are shown on the UIT image in Figure 1. These data are from the same source, a 1985 observation run by P. Massey and K. DeGioia-Eastwood and were reduced and calibrated in a similar manner. In addition to *UBV* photometry, the LH 9 and 10 data also have spectral types for many of the stars in the field (Parker et al. 1992).

The cluster HD 32228 at the core of LH 9 has been omitted from this analysis since the crowded stars therein are unresolved by these observations; cf. the analysis by Parker et al. (1996b) of *HST* observations of HD 32228 and other parts of N 11. These data will be included in a future paper in which we will analyze the entire N 11 region once comparative ground-based data covering the entire UIT field of view have been obtained.

3. THE COLOR-MAGNITUDE DIAGRAM

Stars were matched between the UV and ground-based data using the closest positional coincidence within a 3 pixel (3".4) tolerance, and the observed magnitudes were used to create the observed color-magnitude diagram (CMD) as shown in Figure 3. A large part of the scatter in the CMD is a result of the nonuniform extinction in these regions of roughly $\sigma_{E(B-V)} \sim 0.12$, although intrinsic color variation is probably also a factor.

Reddenings for LH 9, 10, and 13, as determined by ground-based observations, are $E(B - V) = 0.05$, 0.17, and 0.16, respectively (Parker et al. 1992; Degioia-Eastwood et al. 1993). Assuming that the foreground Galactic contribution to the extinction is at least $E(B - V) = 0.05$, we can deredden the observed data by these mean values to obtain the intrinsic CMD, and we find that our data are consistent with the previously published average reddening values. In Figure 3 we
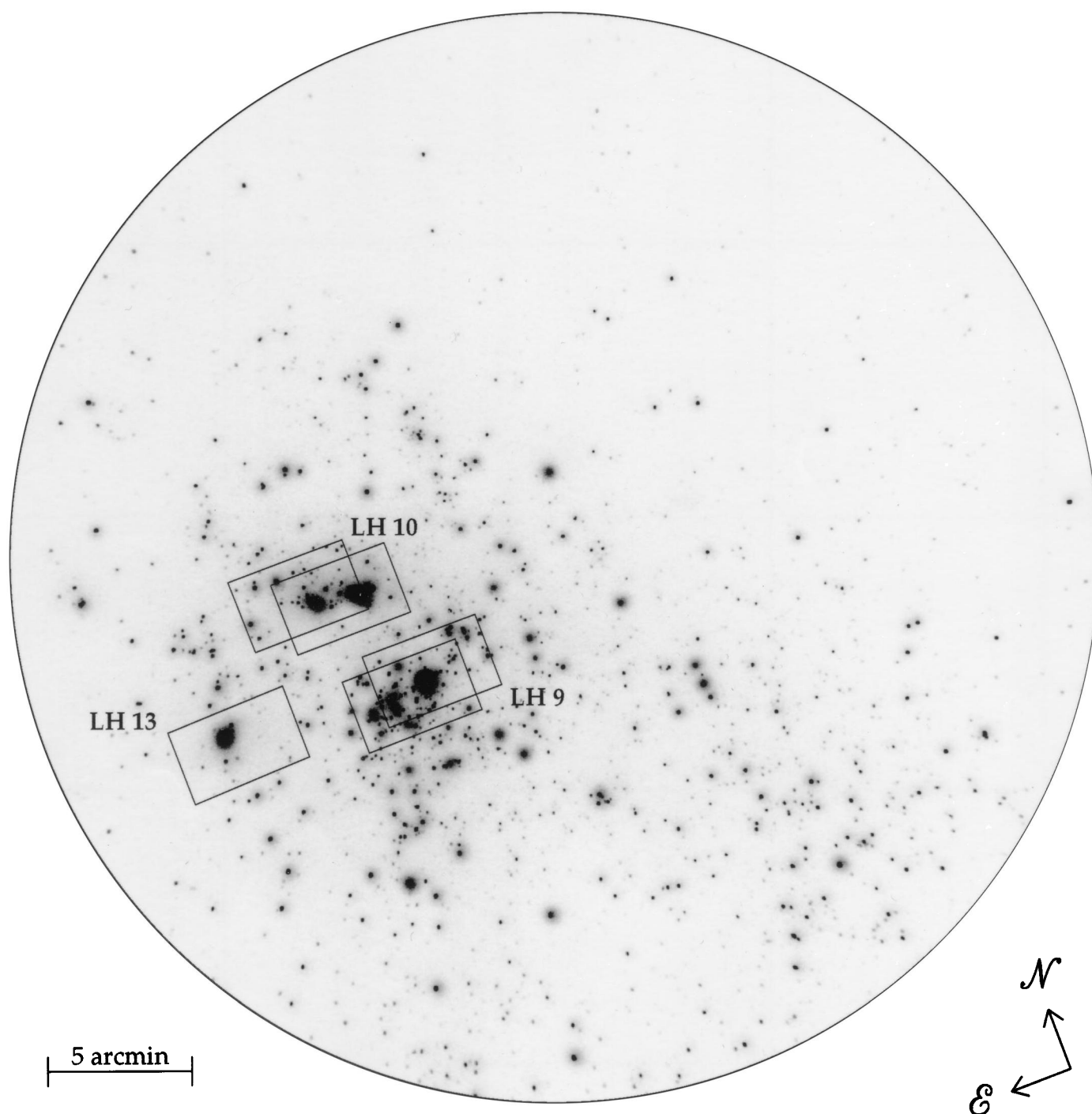
FIG. 1.—986 s exposure UIT image of the N 11 region. Ground-based fields are indicated by outlines.
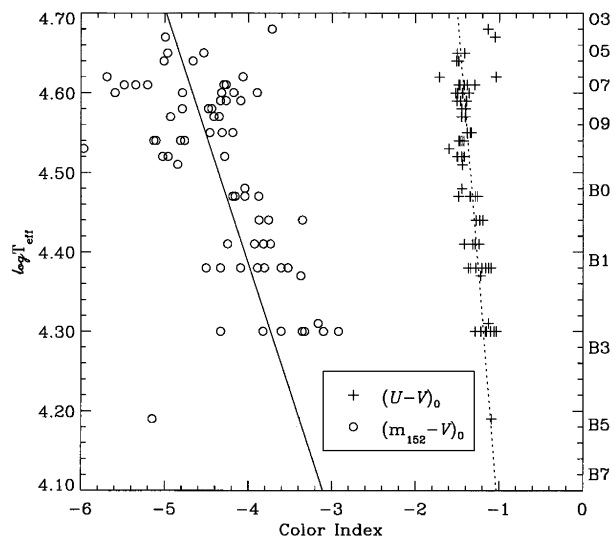
PARKER et al. (see 472, L30)

FIG. 4.—Relationship between stellar temperature (derived from known spectral types) and dereddened color for two color indices: the $U - V$ color (*crosses*) and $m_{152} - V$ color (*open circles*). The linear fit shows that there is very little dependence of the $U - V$ color (*dotted line*) on the temperature for O and at least early B stars, but the $m_{152} - V$ color (*solid line*) shows an appreciable color gradient with temperature.

show the reddening lines for the LMC law and the 30 Doradus law, both from Fitzpatrick (1985). The difference between these laws is too small relative to the scatter of the data to make a definitive determination of the correct reddening law.

The utility of FUV data is shown in Figure 4, where the $(U - V)_0$ and $(m_{152} - V)_0$ color indices are plotted against stellar temperature. The stars were dereddened using individual $E(B - V)$ values calculated by Parker et al. (1992). Only those stars with spectroscopically classified spectral types in LH 9 and 10 are shown in the plot, and temperatures were determined from spectral types independently of any photometric information (Parker et al. 1992). The additional "leverage" of having FUV magnitudes provides a better handle on the temperature (and therefore, spectral type) of the stars than can be obtained from optical data, although there is still a large scatter in even the dereddened $m_{152} - V$ colors. This scatter may be intrinsic but also may be due to the fact that the FUV colors have been dereddened with $E(B - V)$ data, which is not well-defined for hot stars because of the degeneracy in UBV colors. With an FUV extinction of $R_{FUV} = 10.37$, an uncertainty of 0.1 mag in the $E(B - V)$ translates to an uncertainty of over one magnitude in $E(m_{152} - V)$. Blending also affects the scatter, i.e., the star at log $(T_{eff}) = 4.19$ in Figure 4 is a B4 Ia star with a much bluer neighbor that is resolved in the ground-based data but not in the FUV data, so the star's $m_{152} - V$ color appears anomalously blue.

4. THE OB STAR POPULATION OF N 11

CMDs allow us to determine the number of O and B stars in the N 11 region. The dotted line in Figure 3 indicates the 30 Doradus reddening line (Fitzpatrick 1985) for an O9 star using data from Fanelli et al.'s (1992) UV library; the dashed line indicates the LMC law (Fitzpatrick 1985). All of the stars above the reddening line are candidate O stars. A total of 88 stars appear above the LMC reddening line and all have V magnitudes brighter than 16 mag: 48 stars in LH 9 (a lower limit since this does not include stars in HD 32228), 34 stars in LH 10, and 6 stars in LH 13. Only five stars fall between the 30
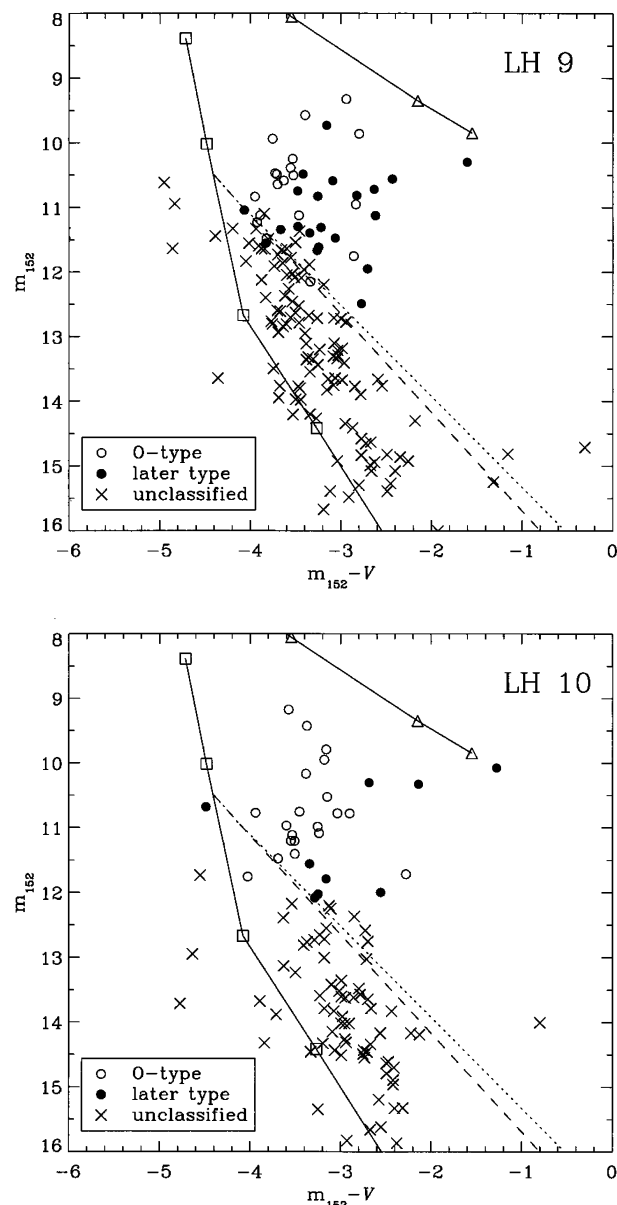

FIG. 5.—Color-magnitude diagrams for LH 9 (*top*) and LH 10 (*bottom*) showing the stars with known spectral types, O-type stars (*open circles*) and later types (*filled circles*), and stars without spectroscopic classifications (*crosses*). The reddening line and intrinsic color lines are the same as in Fig. 3. The majority of unclassified stars are B-type.

Doradus and LMC reddening line, so the results are rather insensitive to the particular law used.

The number of UV-identified O stars can be compared to the number of O stars estimated with ground-based photometry. O stars will have a Q-parameter color of $Q \lesssim -0.85$, where $Q = (U - B) - 0.72(B - V)$, and a visual magnitude of $V < 16$ mag (the unreddened magnitude of an O9 V star in the LMC is roughly 14 mag, so this allows for at least 2 mag. of extinction or $E(B - V) < 0.65$, which is larger than the values found in these regions). Within these limits, 57 candidate O stars are found in the ground-based data: 26 stars in LH 9 (omitting stars in HD 32228), 27 stars in LH 10, and 4 stars in LH 13. A total of 43 O-type stars were classified by Parker et al. (1992) in LH 9 and 10. No classifications have been made for stars in LH 13.

Parker et al. (1992) determined IMF slopes for LH 9 and 10, arguing that the slopes were significantly different, LH 9 being steeper than LH 10, and that this difference may be the product of the different environments in the sequential star formation. However, as discussed above, the FUV data indicate that the number of O stars in LH 9 may be twice the number estimated from the ground-based data, whereas only a few more candidate O stars were found in LH 10 with the FUV data than were found in the ground-based data. At first one might think that this could have the effect of significantly flattening the IMF slope of LH 9 relative to that of LH 10, so that there may be no difference between the slopes. However, as shown in Figure 5, *all* of the unclassified stars are probably late-type O and early-type B stars, since they are positioned at or below the reddening line for an O9 star. The net effect will be to *steepen* the IMF slope of LH 9 and increase the difference with the IMF slope of LH 9. This strengthens the argument that LH 9 and 10 may have experienced differing formation triggers and histories, which could be the result of sequential star formation. Because of the more evolved status of LH 9, there are more B stars above the O9 reddening line than in LH 10.

How many O stars may be in the entire field? This question can be specifically answered once we have obtained ground-based data (giving $m_{152} - V$ colors) for the entire UIT field and follow-up spectroscopy of a selection of the stars to verify these results, but we can make a rough estimate here from the UV magnitudes alone. As can be seen from the CMDs in the figures shown here, most O stars have magnitudes brighter than $m_{152} \sim 12.5$, though some evolved B stars can be as bright as $m_{152} \sim 10.5$. So, the collection of "candidate O-type stars" (COTS) includes not only O-type stars but also stars that have evolved so that they have temperatures of B-type stars but are luminous enough to appear at least as bright in the FUV as the faintest O-type stars. Approximately 30% of all the stars brighter than $m_{152} = 12.5$ in Figure 3 are B stars. This is consistent with Buscombe's (1995; Buscombe & Foster 1994) compilation of stars in clusters with spectral classifications: of all COTS in LMC clusters (a total of 641 stars) listed in that catalog, 36% are luminous (luminosity class I–III) B-type stars.

One might expect the noncluster field stars would have a larger proportion of luminous B stars compared to the stars in clusters. However, the Buscombe (1995) catalog for field stars in the LMC gives nearly the same fraction, 37%, of luminous B stars out of 346 COTS. Similar results are found in the data from Massey et al. (1995), who give spectral types for OB stars in the field and associations of the Magellanic Clouds. Massey et al.'s (1995) "incompleteness fields" in the LMC are a good comparison to the N 11 region since these regions include stars in three possible OB associations as well as stars in the field.

For these regions, out of a total of 43 COTS, 35% of them are B stars. Of all the COTS Massey et al. (1995) classified in the LMC (a total of 136 stars from their Tables 1 and 5), 41% of them are B stars.

Another way to estimate the fraction of B stars in a collection of COTS is to model the distribution assuming an IMF. A star with a zero-age main-sequence mass of about 7 $M_\odot$ (an early B V star) is the lowest mass star that can have a FUV magnitude of $m_{152} < 12.5$ at any point during its lifetime. If one assumes that the O and B stars live about 10% of their lifetimes in an evolved state that is at low enough $T_{\rm eff}$ to be a B star and bright enough to have $m_{152} < 12.5$, then for a typical Salpeter IMF with a slope of $\Gamma = -1.35$, we would find that 25% of the COTS would be classified as B-type stars. Even if one assumes that the IMF slope of the field stars is as steep as $\Gamma = -4.1$ (Massey et al. 1995), 75% of the COTS would be B stars. However, the addition of young, OB associations in the region would significantly lower that percentage.

These comparisons of catalogs and modeling of IMFs show it is not unreasonable to estimate that 30%–50% of the stars in the UIT field brighter than $m_{152} = 12.5$ might be B stars. In the entire UIT image, there are 340 stars brighter than $m_{152} = 12.5$, which implies a total O star population of 170 to 240 stars, four to over five times as many as are currently known in the region.

Although more accurate temperatures and masses of these hot stars can be determined only from time-intensive and methodical classification of spectral types from spectroscopic observations, the UIT data give us the best possible photometrically determined values. From the UIT data we also can obtain the most reliable list of candidate O and B-type stars over an unmatched combination of moderate resolution and large field of view at these wavelengths. Even though this preliminary analysis of the N 11 region is incomplete (pending current programs to obtain ground-based data covering the rest of the UIT field and *HST* observations of the unresolved cluster cores), we have uncovered a surprisingly large number of previously unknown O and B-type stars in this one region alone. This letter provides an exciting example of how UIT's rich data set can be used to obtain unique information on the hot, massive star population of the Magellanic Clouds and other galaxies.

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