RevMexAA (Serie de Conferencias), **8**, 13–20 (1999)

ULTRAVIOLET OBSERVATIONS OF STARS IN THE MAGELLANIC CLOUDS: A HISTORICAL BRIDGE FROM THE SUN TO R136 AND BEYOND

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RESUMEN

Las Nubes de Magallanes nos han proporcionado una perspectiva única sobre las vidas de estrellas de gran masa y han servido de campo de prueba para escenarios de formación y evolución estelar, y para determinar cotas de parámetros estelares. Desde el punto de vista de la observación, las Nubes de Magallanes tienen numerosas ventajas sobre la Galaxia, con una combinación casi ideal de una cantidad comparativamente pequeña (aunque variable) de enrojecimiento en la línea de la visual, diferentes metalicidades y leyes de enrojecimiento, ricas poblaciones de estrellas de masa grande, una distancia relativamente bien conocida para cada galaxia, que además es tal, que permite realizar observaciones, tanto globales como en pequeña escala, de las poblaciones estelares y sus entornos. En la mayoría de los casos, estas propiedades hacen de las Nubes objetivos ideales para la observación UV.

Aquí se revisan las observaciones UV de las Nubes de Magallanes obtenidas en las últimas décadas y de qué modo esos datos han sido herramientas fundamentales en el avance de nuestro conocimiento sobre las estrellas de masas mayores. En particular, se presentan observaciones hechas por el *Ultraviolet Imaging Telescope* (*UIT*), el cual obtuvo datos fotométricos en un extenso campo (sus imágenes tienen un diámetro de 37 minutos de arco). Estos datos son excelentes para destacar estrellas calientes suprimiendo las estrellas más frías y de masas inferiores, que a menudo causan confusión en estudios de campos densamente poblados. Usando los datos de *UIT* se derivan funciones iniciales de masa y otros parámetros para estrellas de campo como también para estrellas en varios cúmulos. En vista a estudios posteriores, se discuten otros usos de estos datos UV y su utilidad para la identificación de poblaciones de estrellas de gran masa en las Nubes.

ABSTRACT

The Magellanic Clouds have provided us with unique insights into the lives of massive stars and have served as test beds for star formation and evolutionary scenarios and for constraining stellar parameters. From an observational point of view, the LMC and SMC have a number of advantages over the Galaxy, with an almost ideal combination of comparatively small (but variable) line-of-sight reddening, different metallicities and reddening laws, rich populations of massive stars, a relatively well-known distance for each galaxy, and such a distance that allows us to make both global and small-scale observations of the stellar populations and their environments. In most cases, these properties make the Clouds ideal targets for UV observations.

I review the last few decades of UV observations of the Magellanic Clouds, and how these data have been instrumental in advancing our knowledge of massive stars. In particular, I present observations made by the *Ultraviolet Imaging Telescope* (*UIT*), which obtained photometric data over a wide field of view (images are 37 arcmin in diameter). These data are excellent at highlighting hot stars while suppressing the cooler, lower mass stars that often cause confusion in studies of crowded fields. Using the *UIT* data, I derive initial mass functions and other parameters for field stars as well as for stars in a collection of clusters. I discuss other uses of these UV data and their utility for identifying populations of massive stars in the Clouds for future studies.

Key words: **MAGELLANIC CLOUDS — OPEN CLUSTERS AND ASSOCIATIONS — STARS: EARLY-TYPE — ULTRAVIOLET: STARS**

1. HISTORY

While preparing for this talk/paper, I wanted not only to present some recent work, but also to put that work in a historical context. The literature trail of ultraviolet (UV) astronomical observations led me back more than a century, and in the first part of this paper, I distill that century to a few pages. It is interesting to show how the initial advances of UV astronomy have taken us above the atmosphere and led us to new and surprising insights into the nature of stars in other galaxies.

1.1. The Ultraviolet and the Earthbound Observer

As was reviewed by Babcock, Moore, & Coffeen (1948), it was not until 1842 when "a rather surprising extent of the ultraviolet region" of the solar spectrum was imaged by Becquerel (1842) and Draper (1843), using flint-glass prisms and daguerreotype plates. Over the next few years, Draper modified techniques and instrumentation to obtain photographs of the solar spectrum to wavelengths below 3360 Å using a diffraction grating and obtaining a reliable wavelength scale (Draper 1845). Draper's work was vastly improved by the work of his son, a fellow named Henry, who pushed the short wavelength limit of the solar spectrum to 3047 Å (Draper 1873a,b).

Subsequent work showed an additional dimension to the short wavelength cutoff of the solar spectrum. In 1878, Cornu moved down another hundred angstroms by measuring the solar spectrum to 2947 Å near sea level (Cornu 1878, 1879), then he recorded solar spectral features down to 2922 Å on the summit of Tenerife (Cornu 1890). These observations conclusively showed that the observed short wavelength limit of the solar spectrum was a function of the amount of atmosphere the light passed through. Finally, in 1921, Fabry & Buisson (1921a,b,c) showed that ozone in the upper atmosphere was the culprit responsible for the abrupt fading of the solar UV spectrum.

Well, this left earthbound observers with the question: "What now?" It seemed that this limit established an insurmountable obstacle to the study of near- and far-UV radiation from extraterrestrial sources.

1.2. Up, Up, and Away

The space UV astrophysics era was born on October 10th, 1946, when the first near-UV observations of the Sun were made by Baum et al. (1946) with a spectrograph mounted on the tail fin of a V-2 rocket launched from the White Sands range in New Mexico. Their instrument recorded data up to an altitude of 88 km, though the rocket was stabilized up to only 44 km. Consequently, their best spectrum down to 2200 Å was obtained at an altitude of 55 km. Many such flights were made in the next few years, but it was not until November 17th, 1955, that the first far-UV (FUV: 1220–1340 Å) observations of non-solar objects were made (Byram et al. 1957). The objects were detected in the Puppis-Vela region, but identification with specific stars was difficult due to the rather coarse resolution of 20 degrees.

These observations set the stage for the explosion in UV space astronomy that was to follow in the next two decades. The observations and instrumentation became more refined. Starting in 1960, Stecher & Milligan (1962) obtained the first FUV (1600–4000 Å) stellar spectra on November 22nd. This feat was accomplished through an improved ability to stabilize and point rockets carrying scientific instruments. Stecher later went on to make the first extinction curves using hot stars as background beacons, and first suggested that carbon was responsible for the 2200 Å bump. Of course, this feature in the UV extinction law has been the focus of later study in the Magellanic Clouds, where its character is quite different than is seen in the Galaxy due to the differing metallicities.

Though they were the key vehicles for FUV astronomy, rockets had limitations, particularly the short amount of time (a few minutes) they provided for observations. During this time, rockets were not the only platform able to get far enough above the atmosphere to make FUV observations; the first FUV astrophysical observations from a high-altitude balloon were made on September 18th, 1968 (Navach, Lehmann, & Huguenin, 1973). Although balloons were not able to go as high as rockets, they provided opportunities for considerably longer integrations. It clearly was time to push FUV astronomy beyond these significant but proportionately small steps above Earth's atmosphere.

1.3. A Giant Leap

Obviously, the next step beyond suborbital rockets would be to place an instrument on an orbiting satellite. But the next accomplishment in UV observations specifically related to the Magellanic Clouds skipped

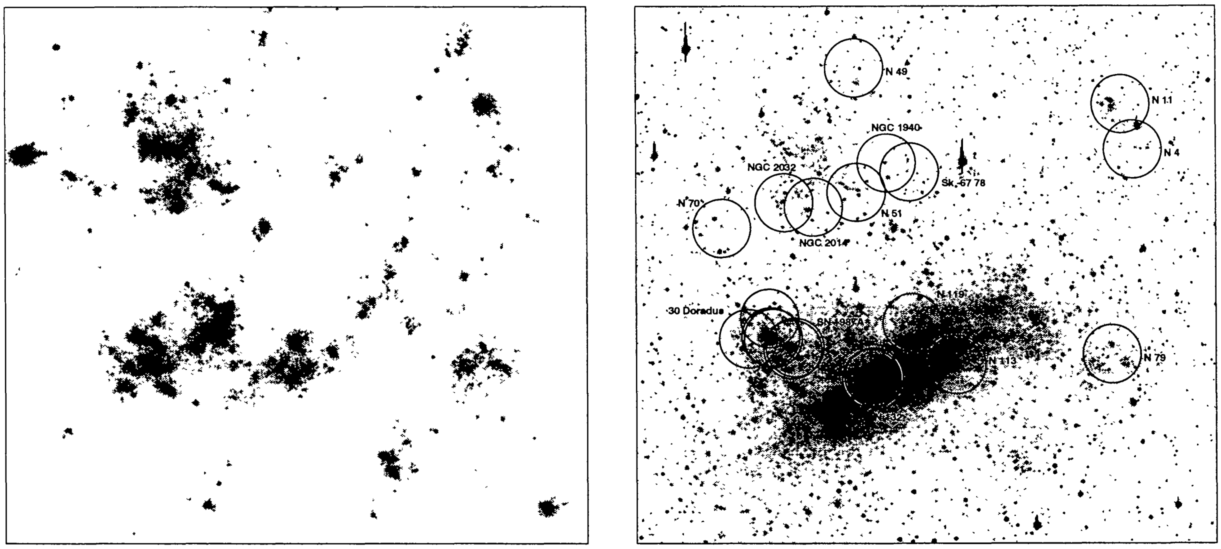

Fig. 1. A comparison of two images of the LMC taken at different wavelengths: A UV rocket image from Smith, Cornett, & Hill (1987) (left) and an *R*-band image from Bothun & Thompson (1988) with the *UIT* fields indicated (right). For scale, the *UIT* fields are 37 arcmin in diameter. Both images have the same spatial scale and orientation of north up and east to the left.

considerably beyond that step. In a giant leap for astronomers, the Magellanic Clouds finally came into UV view in April 1972: The first FUV images and spectra of the LMC were obtained with a Schmidt camera on the Moon (Carruthers & Page 1977, 1984) during the Apollo 16 mission.[1] This first lunar observatory covered the wavelength range 1050–1600 Å over a 20 deg field of view with 3 arcmin resolution. Stars as late as B0 V were detected in the images, which looked similar to the one shown on the left of Figure 1. These images showed that the LMC bar is not prominent in the FUV images, as it is in the visible, and that the FUV surface brightness of the LMC is considerably higher than that of our Galaxy and M31. The spectra provided insights (and fueled further speculation) about reddening in the LMC and effective temperatures and line-blanketing differences between LMC and Galactic stars.

More such observations continued to be made during the reign of the Saturn rockets. Spectra of the LMC also were obtained in December 1972 during the Apollo 17 mission (Henry et al. 1976). Images and spectra of individual O, B, and Wolf-Rayet stars and of the LMC were made with instruments on Skylab (Henize et al. 1975a,b; Vuillemin 1988).

1.4. The Satellite Era

Starting with the launch of Ariel 1 by Great Britain on April 26, 1962, the era of astronomical satellites was born. As can be seen in Table 1, there have been over a dozen significant such satellites with the capability to make observations in the UV and have observed the Magellanic Clouds.

In my opinion, the workhorse of the collection was *IUE*, which made 809 stellar observations of stars in the SMC and 2292 observations of the LMC, averaging about 200 observations of the Clouds each year. The *IUE* archive of UV spectra of stars in the Clouds will continue to be an invaluable resource for years to come. The studies resulting from these observations have provided profound results regarding stellar winds, the evolution of massive stars, reddening laws, and initial mass functions, and have provided libraries for stellar synthesis of starburst galaxies. Now, *HST* continues to make observations of hot and massive stars in the Clouds, giving us more detailed insights into stars in the rich OB associations, and the *HST* archive will leave us with a similarly rich legacy still to be mined.

[1] Although OAO-2 was active before the Apollo 16 mission, I believe it had not yet made any Cloud observations... at least, not that I have found. I would like to hear from someone who can show me otherwise.

TABLE 1

ORBITING OBSERVATORIES THAT MADE UV OBSERVATIONS OF THE MAGELLANIC CLOUDS

Launch Date	Observatory
1968 Dec	Orbiting Astronomical Observatory (OAO-2)
1972 Mar	TD-1A, S2/68
1974 Aug	Netherlands Astronomical Satellite (ANS)
1975 Sep	D2B-AURA, ELZ instrument
1978 Jan	*International Ultraviolet Explorer (IUE)*
1983 Mar	Astron-1 (Soviet astrophysical satellite)
1983 Nov	† Very Wide Field Camera (VWFC)
1987 Mar	Glazar (on the Kvant module of the Mir space station)
1990 Apr	*Hubble Space Telescope (HST)*
1990 Dec, 1995 Mar	† Astro-1 and -2: the *Hopkins Ultraviolet Telescope (HUT)*, the *Ultraviolet Imaging Telescope (UIT)*, and the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE).
1991 Apr	† The FUV Camera (similar to the telescope used on Apollo 16)
1992 Mar	† FAUST
1993 Sep, 1996 Nov	† ORFEUS-SPAS
1997 Aug, 1998 Dec	† Southwest Ultraviolet Imaging System (SWUIS)

NOTE: A dagger (†) indicates a telescope that was flown aboard the space shuttle and made observations only during the duration of the mission.

2. A SPECIFIC EXAMPLE OF CURRENT WORK: *UIT* OBSERVATIONS OF THE MAGELLANIC CLOUDS

2.1. The "Why" and "What" of UIT

Scouting for hot stars is made difficult by the fact that the temperatures of the hottest stars (O and early B-type stars) cannot be accurately measured by standard *UBV* photometry alone (Massey 1985), so unambiguous determination of spectral types and masses is not possible from such data. Perhaps the most reliable, albeit tedious, method of identifying O stars is to use color photometry such as *UBV* magnitudes as a guideline to locate the bluest stars, and then to spectroscopically observe and classify these stars to determine spectral types and, via models, to derive temperatures, luminosities, and masses.

One way to improve on the efficiency of this method is to use UV photometry, which discriminates between the temperatures of the hottest stars better than visible photometry can, but also potentially provides data on hundreds or thousands of stars in the time it takes to get a classification spectrum of a single star. The *Ultraviolet Imaging Telescope* (*UIT*) provides the ability to perform UV photometry in a wide field (37 arcmin diameter) with moderate spatial resolution ($\sim$ 3 arcsec).

During the Spacelab Astro-2 mission, which flew aboard the space shuttle *Endeavour* on 1995 March 2–18, *UIT* obtained more than 700 FUV images of nearly 200 celestial targets. The imaged fields include 16 fields in the LMC (right panel of Figure 1) and three fields in the SMC. During the previous Astro-1 mission on 1990 December 1–10, four fields in the LMC and one field in the SMC were obtained. Populous regions (e.g., 30 Doradus, NGC 330, NGC 346, N 11, and N 51), as well as less crowded clusters and "background" regions, were observed in both galaxies.

The *UIT* observations of the Magellanic Clouds have resulted in catalogs of FUV magnitudes derived from point spread function photometry for 11,306 stars in the SMC (Cornett et al. 1997) and 37,333 stars in the LMC (Parker et al. 1998). The LMC catalog has a completeness limit of $m_{\rm UV} \approx 15$ mag and a detection limit of $m_{\rm UV} \approx 17.5$; the limits for the SMC catalog are about 0.5 mag brighter. The average uncertainty in the photometry is ~ 0.1 mag. The full catalogs with astrometric positions, photometry, and other information are available via publicly available astronomical data archives.

2.2. Comparison of Observations with Models

Regarding the stars in the LMC catalog, we identified those stars that fall within and outside of the DEM (Davies, Elliott, & Meaburn 1976) regions, designating these as "DEM stars" (10,620 stars in the catalog) and "field stars" (26,713 stars in the catalog). We can study these two groupings of stars to determine the underlying initial mass functions (IMFs) by comparing the observed and model luminosity functions (LFs). An observed LF potentially depends on a number of factors, including the slope of the IMF (Γ, where $\Gamma = -1.35$ is the Salpeter (1955) slope), the initial time (t_0) and duration (Δt) of star formation, the metallicity (Z), the stellar upper mass limit ($M_{\rm max}$), the mass loss rate ($\dot{M}$), the reddening [$E(B-V)$], and the binary fraction and mass ratio.

We used an LMC metallicity value of $Z = 0.008$, which is in the range of values of $0.002 < Z < 0.018$ that Kontizas, Kontzias, & Michalitsianos (1993) compiled from the literature (also, conveniently, this is a metallicity for which evolutionary tracks have been tabulated). We should note that metallicity can affect some of the other parameters, particularly $M_{\rm max}$ and $\dot{M}$ (Maeder & Meynet 1994; Meynet 1995). Rotational mixing was not taken into account, although certainly this factor also can have a significant impact on a star's evolution. We did not correct for binaries, though we capriciously assumed that their effect on the comparison of our results to those of other studies which also ignore binaries would be minimal.

In our models, we first assumed a value for the IMF for the mass range 1–120 $M_\odot$, and using the Geneva evolutionary models (Schaerer et al. 1993; Meynet et al. 1994), we evolved stars for each mass bin for the given time range. For each time step and for each mass, we used the resulting evolutionary model parameters to find the appropriate Kurucz (1992) spectrum, which we then convolved with the *UIT* filter functions to obtain the UV magnitudes. The magnitudes were corrected for an LMC distance modulus of 18.5 mag (Panagia et al. 1991). From these model runs, based on input values for the underlying IMF, age, etc., we were able to generate a complete set of luminosity functions for the full range of underlying physical parameters.

As was discussed by Parker et al. (1998), making simple power-law fits to the observed LFs results in a wide range of conflicting results for the underlying IMF if we assume only a linear slope in the LF. To determine the models that best fit the data, we used the multidimensional downhill simplex method (Nelder & Mead 1965), also known as the "amoeba" method (Press et al. 1992), to minimize the residual differences between the distributions. To minimize any bias due to observational limits, we compared the observed and model distributions in the magnitude range 8–14 mag, a range selected to avoid small-number statistics at the bright end, and at the faint end is about one magnitude brighter than the completeness limit. This method was used in over 5000 cases in a Monte Carlo fashion using a wide range of initial values and scale lengths for the free parameters to determine the robustness of the convergence and the best-fit values.

2.3. Field Stars

Our results as shown in Figure 2 give a most likely value for the field star IMF slope of $\Gamma = -1.80 \pm 0.09$, steeper than the Salpeter slope.[2] The peak at this value is highly significant, indicating that the fit to this parameter is extremely good; even though the range of initial values was $-4.5 < \Gamma < 0$ and the area of phase space examined by this method went well beyond even those values, the runs converged very tightly on this result. This result is also independent of the fitting routine, and we found no correlation between this result and the input parameters. The distribution of probable IMF slopes shown in Figure 2 also shows a smaller but still significant peak at $\Gamma = -1.4 \pm 0.02$, roughly equal to the Salpeter slope.

These results are in good agreement with many measurements of the IMF of the LMC field stars (e.g., Bertelli et al. 1992; Westerlund et al. 1995; Vallenari et al. 1996; Gallagher et al. 1996). Cornett et al. (1994) found an essentially equivalent IMF of $\Gamma = -1.7 \pm 0.5$ for the SMC field stars by using *UIT* data. Holtzman et al. (1997) point out that the deep LF for LMC field stars can also be fit with a similar ($\Gamma = -1.75$) IMF if one assumes a younger age for the bulk of field stars. However, Massey et al. (1995) found an unusually steep IMF of $\Gamma = -4.1 \pm 0.2$ for the LMC field stars, which is in strong disagreement with the IMF we find here, regardless of the age or other parameters used in our models.

The reddening and age values did not converge to unique solutions as strongly as the IMF values did, possibly indicating that there is no single best slope or are a few "typical" values.

[2]Those who were at the workshop may notice that the number I quote in this paper for the IMF slope for the field stars is quite different than the value I quoted in my talk. At the workshop, I presented preliminary results, which showed a field star IMF with $\Gamma = -1.35$, *exactly* the value of the Salpeter (1955) slope. I remarked that this agreement seemed embarrassingly fortuitous. Since the time of my talk, we have made recalibrations of the data, adjusted zero points for the photometry, and made bug corrections to the code; it turns out that the agreement *was* just a surprising (and erroneous) coincidence.

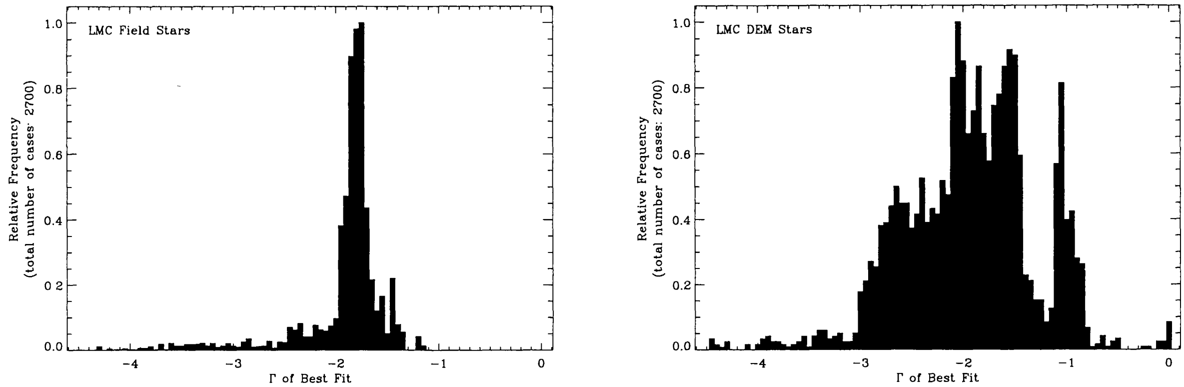

Fig. 2. The frequency histogram of the IMF slope of the best-fit model to the observed stellar LFs in the LMC for the field stars (left panel) and the DEM stars (right panel). This plot indicates the likelihood that all the stars in the analyzed group came from a particular IMF slope. These data are the result of Monte Carlo-type runs with a wide range of values for IMF slope, reddening, age, step, and convergence parameters. For the field stars, the most likely value of the field star IMF slope is $\Gamma = -1.80 \pm 0.09$. The large, narrow peak in this distribution implies that different values for the LMC field star IMF slope are highly inconsistent with our data set. For stars in DEM regions, there is no single, "typical" IMF consistent with these data (grouping the DEM regions as a whole). The three most significant peaks are at $\Gamma = -1.0$, -1.6, and -2.0.

2.4. DEM Stars

As can be seen in Figure 2, the results for the IMF of the DEM stars are less definitive than for the field star IMF. Although the most likely value from the fits to the models (the highest peak in the frequency histogram) is about $\Gamma = -2.0$, it is clear that there are multiple components in the probability distribution. There is a clear, isolated peak at $\Gamma = -1.03 \pm 0.11$, and a broad collection of peaks at slopes between $-1.5 > \Gamma > -2.7$. The most significant components are $\Gamma = -1.6 \pm 0.1$ and -2.0 ± 0.1. There is also a narrow peak at $\Gamma \sim -1.8$, which corresponds to the field star result, and a broad, lower "shoulder" consistent with a component at $\Gamma = -2.5 \pm 0.4$.

The peak at $\Gamma \sim -1.0$ seen in Figure 2 is consistent with results found with *UIT* data of the 30 Doradus region; Hill et al. (1994) found a flatter slope for the 30 Doradus cluster stars compared to the nearby field stars. Our results also are consistent with and supported by the ground-based analysis of Parker et al. (1992), which showed that the two neighboring star-formation regions of LH 9 and LH 10 have two different IMF slopes of $\Gamma = -1.6$ and -1.1, respectively, in remarkable agreement with the peak probability values found here. Although most studies of IMFs of OB associations in the Clouds have found slopes $-2 < \Gamma < -1$, a few found slopes as steep as $-2.5 < \Gamma < -2.0$ or steeper (Scalo 1986, 1997).

It is important to note that the many IMF studies of the Clouds have used a wide range of methods and models, some tried to separate field and cluster stars, and some did not use spectroscopic data. The steeper slopes could be due to different methods or biases (e.g., without spectroscopic classification, visual photometry cannot discriminate between O and early B stars, typically causing underestimates of their masses and artificial steepening of the calculated IMF). However, Scalo (1997) analyzed a number of studies that made direct star counts, and he concluded that either the uncertainties are too large for a clear determination of an IMF, or that variations in the IMF are real and not obviously correlated to environmental parameters. Still, it is interesting that our results for IMF slopes show such strong differences between the field stars and the DEM stars.

As in the case of the field stars, the reddening value did not converge to a unique solution, producing an average value of $E(B-V) = 0.18 \pm 0.13$. The best age for the collection of cluster stars was found to be $t_0 \sim 3.4 \pm 1.9$ Myr. This typical age is completely consistent with that expected from a collection of stellar clusters that contain O and B stars. The distribution of best-fit ages has a fairly broad base, ranging up to ~ 70 Myr with smaller secondary peaks at about 12, 25, and 34 Myr.

2.5. H II Regions, OB Associations, and Massive Stars

Kennicutt & Hodge (1986) published Hα fluxes for many DEM regions, which we can compare to the FUV fluxes measured in the *UIT* images over apertures of equal sizes. We compared our Hα/FUV ratios to values derived from evolutionary models of clusters. For those models, we assumed a Salpeter IMF slope in a single burst of star formation with LMC metallicity. The FUV fluxes were determined in the same way as our evolutionary models discussed above. The Hα fluxes were calculated from the Lyman luminosity of the cluster of stars and assuming a radiation-bounded H II region — the Case B scenario originally discussed by Baker & Menzel (1938). The models were reddened by a Galactic foreground of $E(B-V) = 0.05$.

The comparison of these model results to our measured total stellar fluxes shows that the DEM clusters are all younger than $\sim$ 5 Myr, and the "typical" age is on the order of 1–2 Myr if no reddening is applied to the models. A reddening of $E(B-V) = 0.1$ would shift the models such that the typical age of the clusters would be about 3–5 Myr, consistent with the typical age of $t_0 = 3.4 \pm 1.9$ Myr for the DEM stars we discussed in the previous section. If the H II regions are leaky (e.g., Kennicutt et al. 1995; Oey & Kennicutt 1997), then the regions would be even younger according to the models.

We calculated the ratio of the total stellar flux to the integrated aperture flux for our FUV images; about one-quarter of the total FUV flux in a region typically comes from diffuse FUV light. However, quite a few regions have flux ratios very close to unity within the errors, indicating very little contribution from diffuse FUV light in those instances. Sources for the diffuse FUV flux could be either scattered light or the light from a population of stars fainter than our point spread function photometry limit. If the light is from faint stars, then the fact that some of the DEM regions have stellar-to-integrated flux ratios close to unity would imply that some regions do *not* have significant populations of such fainter (lower mass) stars. However, there is no obvious correlation between brightness of the region and the flux ratio, which argues against the diffuse flux being due to a constant spatial distribution of faint stars. It also means that the brighter (presumably more active and populous) regions do not have proportionately greater or fewer faint, unresolved stars, e.g., there is not a low-mass cutoff or increase in the star formation activity within the detection limits of the diffuse flux. Cornett et al. (1997) found ratios for the stellar to integrated flux in the SMC to be somewhat lower than we found in these LMC regions, and argued that dust-scattered radiation is a major contributor to the diffuse flux.

We can estimate the number of OB stars in the clusters and the field from these UV data. Parker et al. (1996) showed that most O stars in the LMC region N 11 had observed (reddened) UV magnitudes brighter than $\sim$ 12.5, though some evolved B stars can be as bright as $\sim$ 10.5. Their comparisons with models and catalogs showed that 50% to 70% of the stars brighter than 12.5 mag should be O-type stars. Using these parameters, we find 1100–1500 candidate O-type stars in the DEM regions, and 1600–2300 such stars in the general field.

These results for *UIT* provide just one example of the wealth of information that can be obtained from UV observations of massive stars in the Magellanic Clouds. A more complete treatment would discuss in detail the discoveries made by other instruments, as well as the comparison of the primarily stellar-specific results of UV observations with observations of the ISM. Such an analysis would help us to understand the life cycles of stars, their impact on their environment, and the ecology of the Clouds as complete galaxies.

REFERENCES

Babcock, H. D., Moore, C. E., & Coffeen, M. F. 1948, ApJ, 107, 287
Baker, J. G., & Menzel, D. H. 1938, ApJ, 88, 52
Baum, W. A., Johnson, F. S., Oberly, J. J., Rockwood, C. C., Strain, C. V., & Tousey, R. 1946, Phys. Rev., 70, 781
Becquerel, E. 1842, Bibliothèque Universelle de Genève, 40, 341
Bertelli, G., Mateo, M., Chiosi, C., & Bressan, A. 1992, ApJ, 388, 400
Bothun, G. D., & Thompson, I. B. 1988, AJ, 96, 877
Byram, E. T., Chubb, T. A., Friedman, H., & Kupperian, J. E., Jr. 1957, AJ, 62, 9
Carruthers, G. R., & Page, T. 1977, ApJ, 211, 728
__________. 1984, PASP, 96, 447
Cornett, R. H., Hill, J. K., Bohlin, R. C., O'Connell, R. W., Roberts, M. S., Smith, A. M., & Stecher, T. P. 1994, ApJ, 430, L117
Cornett, R. H., Greason, M. R., Hill, J. K., Parker, J. Wm., & Waller, W. H. 1997, AJ, 113, 1011
Cornu, A. 1878, C. R. Acad. Sci., 86, 1101
__________. 1879, C. R. Acad. Sci., 89, 808
__________. 1890, C. R. Acad. Sci., 111, 941
Davies, R. D., Elliott, K. H., & Meaburn, J. 1976, MmRAS, 81, 89 (DEM)
Draper, H. 1873a, Amer. J. Sci., 6, 401
__________. 1873b, Phil. Mag., 46, 417
__________. 1843, Phil. Mag., 22, 360

_________. 1845, Phil. Mag., 26, 465
Fabry, Ch., & Buisson, H. 1921a, J. de Phys. 2, 197
_________. 1921b, J. de Phys. 2, 297
_________. 1921c, ApJ, 54, 297
Gallagher, J. S., et al. 1996, ApJ, 466, 732
Henize, K. G., Wray, J. D., Parsons, S. B., Benedict, G. F., Bruhweiler, F. C., & Rybski, P. M. 1975a, ApJ, 199, 119L
Henize, K. G., Wray, J. D., Parsons, S. B., & Benedict, G. F. 1975b, ApJ, 199, 173L
Henry, R. C., Feldman, P. D., & Fastie, W. G. 1976, A&A, 53, 317
Hill, J. K., Isensee, J. E., Cornett, R. H., Bohlin, R. C., O'Connell, R. W., Roberts, M. S., Smith, A. M., & Stecher, T. P. 1994, ApJ, 425, 122
Holtzman, J. A., et al. 1997, AJ, 113, 656
Kennicutt, R. C., Bresolin, F., Bomans, D. J., Bothun, G. D., & Thompson, I. B. 1995, AJ, 109, 594
Kennicutt, R. C., & Hodge, P. W. 1986, ApJ, 306, 130
Kontizas, M., Kontizas, E., & Michalitsianos, A. G. 1993, A&A, 269, 107
Kurucz, R. L. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 255
Maeder, A., & Meynet, G. 1994, A&A, 287, 803
Massey, P. 1985, PASP, 97, 5
Massey, P., Lang, C. C., DeGioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188
Meynet, G. 1995, A&A, 298, 767
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Navach, C., Lehmann, M., & Huguenin, D. 1973, A&A, 22, 361
Nelder, J. A., & Mead, R. 1965, Comp. J., 7, 308
Oey, M. S., & Kennicutt, R. C. 1997, MNRAS, 291, 827
Panagia, N., Gilmozzi, R., Macchetto, F., Adorf, H.-M., & Kirshner, R. P. 1991, ApJ, 380, L23
Parker, J. Wm., Garmany, C. D., Massey, P., & Walborn, N. R. 1992, AJ, 103, 1205
Parker, J. Wm., Hill, J. K., Bohlin, R. C., O'Connell, R. W., Neff, S. G., Roberts, M. S., Smith, A. M., & Stecher, T. P. 1996, ApJ, 472, L29
Parker, J. Wm., et al. 1998, AJ, 116, 180
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in Fortran: The Art of Scientific Computing, (Cambridge: Cambridge Univ. Press)
Salpeter, E. E. 1955, ApJ, 121, 161
Scalo, J. M. 1986, Fundam. Cosmic Phys., 11, 1
_________. 1997, preprint
Schaerer, D., Meynet, G., Maeder, A., & Schaller, G. 1993, A&AS, 98, 523
Smith, A. M., Cornett, R. H., & Hill, R. S. 1987, ApJ, 320, 609
Stecher, T. P, & Milligan, J. E. 1962, ApJ, 136, 1
Vallenari, A., Chiosi, C., Bertelli, G., Aparicio, A., & Ortolani, S. 1996, A&A, 309, 367
Vuillemin, A. 1988, A&AS, 72, 249
Westerlund, B. E., Linde, P., & Lynga, G. 1995, A&A, 298, 39