

CR-189324

Contract S-97230E
Task Assignment 3041-001
Final Report

Voyager Observations of Globular Clusters.

Task objectives:

The objectives of this task are to direct and analyse the observations of globular clusters targets observed with the Ultraviolet Spectrometer on the Voyager spacecraft. The data analysis will be directed toward understanding the Voyager spectra or upper limits in terms of the expected properties of the hot stars in the globular clusters.

Summary of Work Performed:

One out of the four proposed targets was observed before the Voyager guest observer program was canceled in early 1993. The observed target, NGC 6397, showed a spectrum characteristic of hot stars. However, further analysis showed that most of this emission was unlikely to be due to the hot post asymptotic giant branch cluster member ROB 162, and was probably due to dust-scattered light from unrelated foreground stars.

Three types of analysis were performed to test the origin of the Voyager spectrum. First, the flux variations during the limit-cycle motion of the spacecraft motion were binned as a function of time; these showed no evidence of a point source response. Second, the Voyager spectrum were compared with an IUE spectrum of ROB 162; this showed that the Voyager flux was three times larger than could be explained from this star alone. Finally, a Voyager background observation taken 26 arcminutes from the cluster center was analyzed; this showed that the observed spectrum intensity did not diminish as the Voyager aperture was moved away from the globular cluster center.

A summary of the Voyager results was included in a talk titled, "UV-bright Stars in Globular Clusters" at a meeting "Hot Stars in the Halo" which was held at Union College in Albany, NY on Nov. 4-5, 1993. The results were then written up for the proceedings to this conference, and are included here as Appendix 1.

(NASA-CR-189324) UV-BRIGHT STARS
IN GLOBULAR CLUSTERS (Hughes STX)
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UV-bright Stars in Globular Clusters

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I highlight some recent work based on ultraviolet observations of globular clusters. Images of the globular clusters M79, NGC 1851, ω Cen, M3, and M13 were obtained with the Ultraviolet Imaging Telescope (UIT) in 1990 December. The blue and extreme horizontal branch (HB) stars in M79, ω Cen, and NGC 1851 are found to be 0.2 - 0.5 mag fainter than predicted by HB models using nominal distances and reddening. The origin of this discrepancy is not yet understood. In NGC 1851, two hot ($T_{eff} > 20,000$ K) subdwarfs have been identified, and one has been confirmed as a radial velocity member by followup ground-based spectroscopy. Since NGC 1851 does not have an extended horizontal branch, these stars are unlikely to be a product of single star evolution. Several candidate UV-bright stars in M79 and ω Cen are identified on the UIT images, and a program of IUE and optical followup spectroscopy is in progress. Of particular interest is ROA 5342 in ω Cen, which is identified as a sdO cluster member from ground-based spectroscopy.

Observations of NGC 6397 were obtained with the Ultraviolet Spectrometer on the Voyager 2 spacecraft. Although a hot stellar-like spectrum is detected, the dominant source of this emission is probably dust scattered light from hot foreground stars, unrelated to NGC 6397.

1. Introduction

Ultraviolet images of globular clusters have a strikingly different appearance from ground-based images. At 1500 Å, all stars cooler than ~ 7500 K are suppressed, including the main sequence stars, the red giant and asymptotic giant branch (AGB) stars, and the RR Lyrae and red horizontal branch (HB) stars. Even the contamination due to foreground stars is strongly suppressed. What remains on an ultraviolet image are the hot HB stars, and an occasional luminous hot post-AGB star. Ultraviolet imagery is thus an excellent tool for the discovery of hot stars in globular clusters, and for study of their radial distribution and fundamental parameters.

Ultraviolet images of five globular clusters were obtained with the Ultraviolet Imaging Telescope (UIT) during the first flight of the *Astro* observatory in 1990 December (Stecher *et al.* 1992). The UIT images are recorded on image-intensified film with about 3" spatial resolution. The observed clusters span a narrow range in metallicity (Table 1), but are useful for the second-parameter studies, since ω Cen, M79, and M13 contain an extended tail of hot HB stars, while NGC 1851 and M3 do not. The images of ω Cen, M3, and M13 were obtained on the daytime side of the Shuttle orbit, and were successfully observed only with a single anti-dayglow filter centered at 1620 Å, while M79 and NGC 1851 were observed with two broad-band filters centered at 1520 Å and 2490 Å.

This paper highlights globular cluster studies with UIT in three areas: (1) the discrepancy between observed ultraviolet HB magnitudes and predictions of theoretical HB models (2) the discovery of two hot subdwarfs in NGC 1851, a globular not previously known to contain such stars, and (3) spectroscopic followup of newly identified UV-bright stars in M79 and ω Cen. I also present results of a recent observation of NGC 6397 with the Voyager ultraviolet spectrometer.

| Name | (m-M) ₀ | E(B-V) | [Fe/H] | Exp Time (s) | Comment |
|--------------|--------------------|--------|--------|-----------------|---------|
| M79 | 15.57 | 0.01 | -1.69 | 1116 | |
| NGC 1851 | 15.49 | 0.02 | -1.29 | 543 | |
| ω Cen | 13.45 | 0.15 | -1.59 | 291 | Daytime |
| M3 | 15.02 | 0.01 | -1.66 | 199 | Daytime |
| M13 | 14.29 | 0.02 | -1.65 | 46 | Daytime |

Table 1. Globular clusters observed with UIT

2. Absolute luminosity of the ZAHB

Based on the LTE stellar atmospheres of Kurucz (1992), the ultraviolet fluxes of the hot ($T_{eff} > 10000$ K), high-gravity ($\log g > 4$) stars on the blue horizontal branch are predicted to have only a very weak dependence on metallicity and gravity. For example, the UIT 1620 Å flux of a solar metallicity Kurucz model with $T_{eff} = 20,000$ K differs by only 0.03 mag from a model with the same T_{eff} but with $\log Z/Z_{\odot} = -3$. Therefore, the transformation of a UV color-magnitude diagram to a theoretical (T_{eff} , log L) diagram should be especially secure. Thus, we were surprised to discover that for both NGC 1851 (Parise *et al.* 1994) and ω Cen (Whitney *et al.* 1994) the blue HB stars observed by UIT are approximately 0.5 mag fainter than predicted by current zero-age horizontal branch (ZAHB) models, using the nominal cluster distances, reddenings and metallicities given in Table 1. A somewhat smaller discrepancy of 0.2–0.3 mag is found for the M79 ultraviolet color-magnitude diagram (Hill *et al.* 1992).

The discrepancy of the UIT fluxes with the theoretical ZAHB in NGC 1851 and ω Cen could be removed by increasing the assumed cluster reddening E(B-V) values by 0.1 mag, by assuming extremely steep ultraviolet extinction properties of the interstellar dust, such as that found in the Small Magellanic Clouds, or by increasing the cluster distance moduli by 0.5 mag. Alternatively, the ZAHB models could be made 0.5 mag fainter if the adopted helium core mass were decreased from its canonical value by $\sim 0.05 M_{\odot}$ (Sweigart 1994). Another way to remove the discrepancy is to suppose that most of the hot stars seen by UIT are not the product of single star evolution, so that standard HB models do not apply. Strong criticisms can be made against each of these scenarios, which appear to conflict with a variety of measurements at other wavelengths. Note, however, that Noble *et al.* (1991) and Nemec *et al.* (1993) argue for a larger distance modulus for ω Cen, and that there have been several claims in the literature of a larger reddening toward NGC 1851, as reviewed – but not endorsed – by Walker (1992).

Could there be an offset of 0.5 magnitudes in the UIT calibration? The absolute calibration of UIT is mainly based on comparison of ~ 20 stars observed in common with IUE. However, the linearity of UIT must also be verified, since the HB stars are typically ~ 5 magnitudes fainter than the IUE calibration stars. Extensive tests on UIT images of differing exposure times have revealed some linearity problems, but at a less than 10% level. The current UIT calibration is especially convincing for ω Cen, where there are several long IUE exposures of UV-bright stars in the cluster. Verification of the UIT fluxes may be possible with observations of blue HB stars with the Faint Object Spectrograph on HST, or with the reflight of the *Astro* mission in December 1994, when several additional UIT globular cluster pointings are planned.

| Name | m_{1520} | m_{2490} | V | B-V | Comment |
|--------|------------|------------|------|-------|--------------|
| UIT-44 | 15.9 | 17.3 | 18.6 | 0.11 | RV member |
| UIT-31 | 16.1 | 17.1 | 18.6 | -0.22 | =Walker 1243 |

Table 2. Hot Subdwarfs in NGC 1851

3. Hot Subdwarfs in NGC 1851

Parise *et al.* (1994) identified 46 blue horizontal branch stars outside of the central $70''$ in NGC 1851 on UIT images at 2490 Å and 1520 Å. (The core of the cluster could not be studied since it is heavily saturated by the presence of the luminous hot post-AGB star UV-5.) Two of these stars, UIT-44 and UIT-31, showed $m_{2490} - m_{1520}$ colors indicating effective temperatures greater than 20,000 K. This result was somewhat surprising because ground-based studies of NGC 1851 had not shown the presence of a hot extended HB. The recent study of Walker (1992) confirmed a bimodal temperature distribution of HB stars, but with only 27% of the HB stars blueward of the RR Lyrae gap, and none hotter than 10,000 K. Landsman *et al.* (1994a) obtained CTIO spectrophotometry of UIT-44 and confirmed it as a radial velocity cluster member. The spectrum showed only weak Balmer lines typical of helium-poor hot subdwarfs. Simultaneous model fitting of the Balmer lines yielded $T_{eff} = 29700 \pm 1630$ K and $\log g = 5.39 \pm 0.27$.

Table 2 gives the visible and ultraviolet photometry for the two hot subdwarfs in NGC 1851. The V and B-V magnitudes for UIT-44 are from the CCD photometry in Landsman *et al.* (1994a), while the values for UIT-31 are from the Walker (1992) catalog. While UIT-31 is not a confirmed cluster member, the similarity of its ultraviolet magnitudes and color to UIT-44 strongly suggest membership. The presence of these two stars is not easily explained by models of single star evolution, since a mechanism must be found to explain their large separation in effective temperature from other HB stars in the cluster. Possible evidence for the binarity of UIT-44 is its observed value of $B-V = 0.11$, which is too red to be compatible with the ultraviolet photometry or the temperature derived from Balmer line fitting.

4. UV-bright Stars

The term "UV-bright star" is used here to refer to a star more than ~ 1 magnitude brighter than the observed ZAHB luminosity. This definition is motivated by theoretical tracks which predict that hot HB stars will be ~ 1 magnitude brighter than the ZAHB at the time of their core helium exhaustion (Dorman, Rood, & O'Connell 1993). The scenario where most hot UV-bright stars are evolved off of the extended HB (i.e. AGB-manque stars) is consistent with the absence of UV-bright stars found on the UIT image of NGC 1851 (except for the known post-AGB star UV5). On the other hand, about 30 UV-bright stars are visible on the UIT image of ω Cen, and Hill *et al.* (1992) identified two UV-bright stars on the M79 images. The tracks of Dorman *et al.* predict that the number of UV-bright stars should be 15–20% of the number of core helium burning stars on the extended HB, and this is roughly what is observed in the ultraviolet color-magnitude diagram of ω Cen (Whitney *et al.* 1994).

We have begun a program of ground-based and IUE spectroscopy of the UV-bright stars discovered on the UIT images of M79 and ω Cen. Tables 3 and 4 list the stars for which either optical or IUE observations are already available, although in most cases, our analysis is still preliminary. The listed luminosities and temperatures are estimated

| Name | m ₁₅₂₀ | m ₂₄₉₀ | V | B-V | T _{eff} | l _{bol} |
|--------------|-------------------|-------------------|-------|-------|------------------|------------------|
| UIT-1(F1179) | 13.4 | 14.4 | 18.61 | -0.28 | > 40000 | > 2.4 |
| UIT-2(F2804) | 14.2 | 14.5 | 16.83 | -0.09 | 13000 | 2.0 |

Table 3. Newly identified UV-bright stars in M79

| Name | m ₁₆₂₀ | V | B-V | Sp.T. | T _{eff} | l _{bol} |
|---------|-------------------|-------|-------|--------|------------------|------------------|
| UIT-1 | 10.8 | | | B-type | 18000 | 2.9 |
| UIT-2 | 11.9 | | | B-type | 19000 | 2.5 |
| ROA5342 | 12.2 | 15.89 | -0.15 | sdO | > 40000 | > 2.6 |
| ROA5857 | 12.9 | 15.37 | 0.04 | HBB | 16000 | 2.1 |
| Dk 3873 | 12.9 | 16.00 | 0.04 | sdO? | > 20000 | > 2.1 |

Table 4. Newly identified UV-bright stars in Omega Cen

from the UV and visible photometry, and the adopted cluster distances and reddenings in Table 1. For the hotter stars, the value of T_{eff} derived this way is very sensitive to errors in the photometry or the assumed reddening, and only lower limits are given. In M79, the optical identifications and V and B-V magnitudes are taken from the catalog of Ferraro *et al.* (1992). Further discussion of the IUE and optical spectra of the M79 stars will be given in Cheng *et al.* (1994)

IUE spectra of the stars UIT-1 and UIT-2 in ω Cen were discussed by Landsman *et al.* (1992). Both stars show low-resolution IUE spectra similar to those of main-sequence B-type stars, but with weaker absorption lines. Unfortunately, ground-based spectroscopy of these stars may not be possible, because they are within 2' of the dense cluster center. The identifications and V and B-V magnitudes for the other three UV-bright stars in ω Cen are taken from Dickens *et al.* (1988). Low-resolution spectroscopy of ROA 5342 and ROA 5857 at CTIO confirm both stars as radial velocity cluster members. ROA 5857 has a luminous BHB-type spectrum with strong Balmer lines visible up to $n=12$. ROA 5342 has an sdO spectrum with Balmer lines accompanied by He II absorption (Figure 1). The equivalent widths of the He II lines closely match those of the sdO star ROB 162 in NGC 6397 (Heber & Kudritzki 1986). This suggests that ROA 5342 that might be similar to ROB 162 in having a normal helium abundance and a post-AGB evolutionary status. The IUE spectrum of ROA 5342 (Figure 2) shows weak emission features near He II 1640 Å and C III 1909 Å, which might indicate an associated planetary nebula. We are preparing a more detailed investigation of ROA 5342 (Landsman *et al.* 1994b), and have recently obtained an echelle spectrum at the CTIO 4-m.

No optical spectra were obtained of Dk 3873. However, its IUE spectrum matches quite closely to that of ROA 5342 (Figure 3), which is suggestive both of its cluster membership and of its high effective temperature.

5. Far-UV Observations

The 912–1216 Å region can provide a sensitive measure of the effective temperature of stars with $T_{eff} > 25,000$, for which the flux longward of Ly α is a poor discriminator. There have been successful programs with both the HUT and Voyager ultraviolet spectrometers to detect globular clusters shortward of 1216 Å. The Hopkins Ultraviolet Telescope (HUT) was co-pointed with UIT during the *Astro-1* mission and obtained 912 – 1860 Å spectra of hot stars in M79, M3, and NGC 1851 (Dixon, Davidsen, & Ferguson

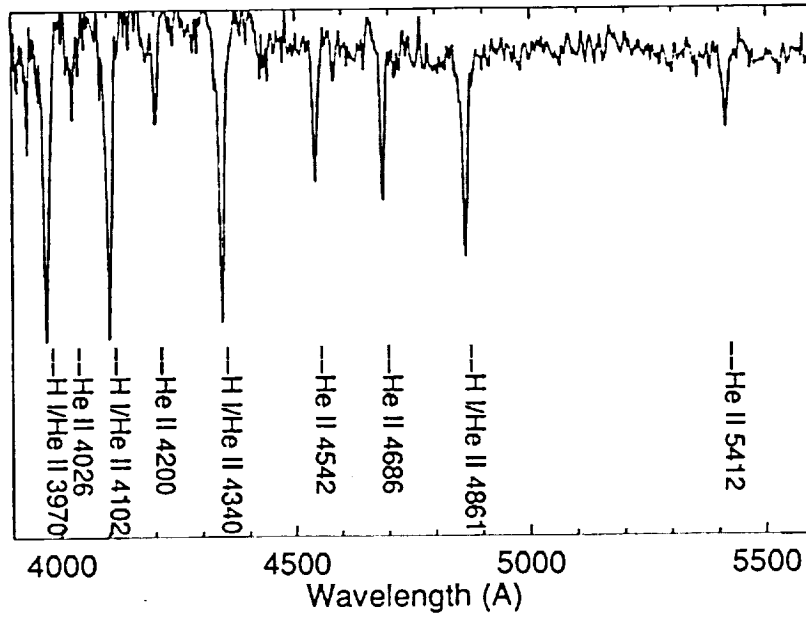


Figure 1. A rectified CTIO spectrum of ROA 5342 in ω Cen

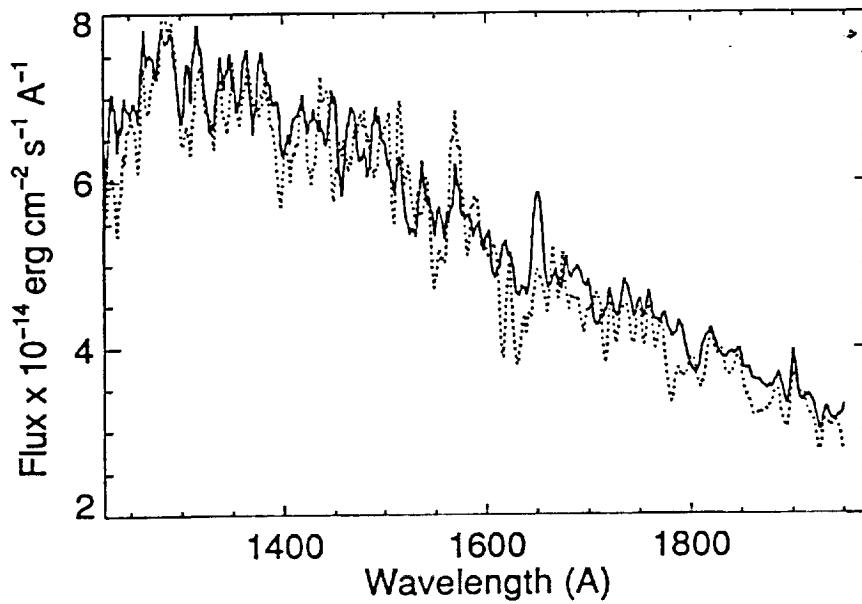


Figure 2. IUE spectrum SWP 48266 of ROA 5342 (solid line), and SWP 48271 of Dk 3873 (dotted line). The Dk 3873 spectrum has been multiplied by a factor of 1.6.

1994). In M79, the HUT large (18" × 116") aperture was used to integrate the flux of numerous blue and extended horizontal branch stars, while in M3 and NGC 1851, the HUT aperture was centered, respectively, on the hot post-AGB stars, vZ1128 and NGC 1851. The Voyager ultraviolet spectrometer was used to obtain 912 – 1700 Å spectra of the clusters NGC 6752, M13 and M92 (Holberg 1990a). The 0.1° × 0.87° Voyager FOV is well-matched to globular clusters, and partially compensates for its limited sensitivity ($\sim 5 \times 10^{-13}$ erg cm⁻² s⁻¹ Å⁻¹).

Only one additional globular was observed with Voyager before the guest observer program was canceled in early 1993. Figure 2 shows a Voyager 2 spectrum of NGC 6397 obtained during 5 days of integration in February 1993. The horizontal branch of NGC 6397 does not contain an extended blue tail (Alcaino *et al.* 1987), and so the dominant contribution to the Voyager spectrum was expected to be from the well-studied hot post-AGB star ROB 162 (Heber & Kudritzki 1986). However, there are three reasons to believe that ROB 162 was *not* the main contributor to the Voyager spectrum. First, the Voyager flux longward of Ly α is ~ 3 times larger than the IUE flux of ROB 162. Second, there was no evidence of a point-source response during the limit cycle motion of the spacecraft. Finally, a Voyager "background" observation at an offset position 26' from the cluster center shows a similarly strong spectrum.

The source of the diffuse emission detected by Voyager is probably dust scattered starlight unrelated to NGC 6397. Such diffuse galactic light has been detected by Voyager at similar intensities at other locations at low galactic latitude (Holberg 1990b). (The galactic latitude of NGC 6397 is -12°.) Thus, the measurement of the 912-1200 Å spectrum of ROB 162 must wait for future spectrographs with smaller apertures, such as the reflight of HUT in December 1994 on the *Astro-2* mission.

This paper summarizes work done with various collaborators including K.-P. Cheng, Van Dixon, Bob Hill, Paul Hintzen, Bob O'Connell, Ron Parise, Rex Saffer, Ted Stecher, and Jon Whitney. I thank Jay Holberg for assistance with the Voyager data reduction. This work is supported by NASA Voyager grant S-97230E to Hughes STX.

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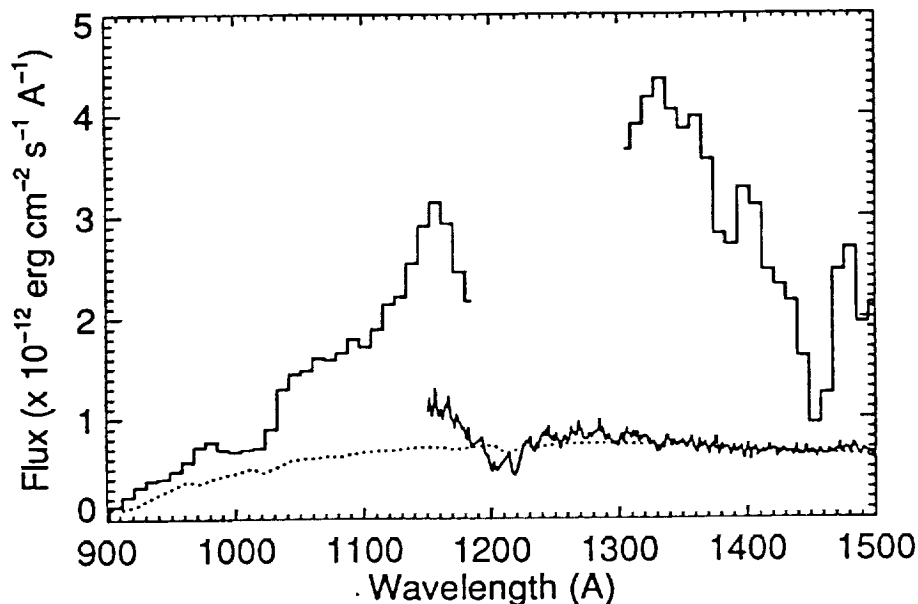


Figure 3. Voyager spectrum of NGC 6397; the spectral region contaminated by diffuse interplanetary Ly α has been deleted. Also shown is an IUE spectrum (SWP 15322) of the hot post-AGB star ROB 162. The dotted line shows a Kurucz (1992) model with $T_{eff} = 50,000$ K, $\log g = 4.5$, and $\log Z/Z_{\odot} = -1$ which has been normalized to the $V = 13.23$ magnitude of ROB 162 and reddened with $E(B-V) = 0.18$. The parameters used for the Kurucz model are those determined spectroscopically for ROB 162 by Heber & Kudritzki (1986).

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