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OBSERVATIONS OF THE LIGHT ECHOES FROM SN 1987A USING THE *ASTRO-1* ULTRAVIOLET IMAGING TELESCOPE

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ABSTRACT

We present the results from images taken of the region of the light echoes around SN 1987A, as acquired on the first flight of the *Astro-1* Ultraviolet Imaging Telescope (UIT). They indicate a weighted-average ultraviolet echo surface brightness of $\approx 3 \times 10^{-18}$ ergs s^{-1} cm^{-2} Å^{-1} arcsec^{-2}. This is consistent with earlier results obtained by the *International Ultraviolet Explorer*, when scaled by the optical surface brightnesses of the two different echoes observed. These results indicate that the ultraviolet flux emitted by the shock from core collapse penetrating the stellar surface cannot be as strong as that predicted by a large class of theoretical models (cited herein), or that previous results on the optical scattering of echoing dust do not apply to these clouds. Prospects for a more accurate measurement, once the echoes have propagated to other regions and a background measurement can be obtained with UIT, are discussed. They indicate that a more accurate determination of the above results is probable with another epoch of UIT observations.

Subject headings: dust: extinction — supernovae: individual (SN 1987A) — ultraviolet: stars

1. INTRODUCTION

Light echoes (transient reflection nebulae) carry with them extensive amounts of unique information regarding the geometry, distribution, and scattering properties of the reflecting dust clouds, as well as the nature of the incident radiation being scattered. With the explosion of SN 1987A, we have observed the first extensively spatially resolved echoes (Crotts 1988; Gouiffes et al. 1988; Suntzeff et al. 1988) since Nova 1901 Persei (Ritchey 1902; Perrine 1903), and the first such echoes from a supernova.

In the case of SN 1987A, the light echoes have the potential of supplying crucial data for understanding the supernova itself. Even though the first record of the explosion by I. Shelton occurred very early after core collapse (cf. Arnett 1988), very few data were obtained in the first 24 hours, particularly in the ultraviolet, where most of the electromagnetic radiation escaped (Chevalier & Fransson 1987). The echoes, however, contain a record of the flux emitted during the entire event, even the first moments of shock breakout through the stellar surface. Since the effective temperature in the first hours was likely in the vicinity of several times 10^5 K, most of that echo should be evident at suboptical wavelengths. Indeed, the Ultraviolet Imaging Telescope (UIT) was identified as an instrument capable of obtaining useful data on the echoes from shock breakout (Chevalier & Emmering 1988).

An additional motivation for studying the UV echoes, but a complicating factor in determining the shock breakout flux, is the likelihood of strong forward scattering in the ultraviolet. Whereas the echo colors appear consistent with Rayleigh scattering in the optical/near-IR wavelength range 400–1000 nm (Suntzeff et al. 1988; Crotts 1988), there is no indication that this is the case for wavelengths several times shorter. The narrow-angle scattering phase function of interstellar dust in the ultraviolet is constrained by only very recent data (Witt et al. 1991) and might be improved. In particular, the strength of forward scattering in the UV might be measured directly rather than in comparison to scattering in the optical.

The echoes' scattering angles can be determined from imaging data and tend to be small for the interstellar echoes. The scattering angle is calculated directly by the angular radius of the echo with respect to the supernova (SN) and the time delay between the observation of the direct radiation from the SN and the echoed radiation. The scattering angle is given by $\alpha = \cos^{-1}(z/R)$, where $R = z + ct$, $z = r^2/2ct - ct/2$, and $r = D \sin \theta$. (D is the distance to the SN, t the delay time, and θ the observed angular separation between the echo and the SN.) The distances of the prominently echoing interstellar clouds are $z = 400$ and 1040 lt-yr in front of the SN, so at the epoch of observation by UIT (day 1403 after shock breakout) the scattering angles are only $\alpha = 7.^{\circ}9$ and $4.^{\circ}9$, respectively. By measuring the surface brightness at specific scattering angles, we determine the product of the dust density, $Q_{\rm scat}$, and the phase function. Making the assumption that the dust is similar at various points in the clouds, and comparing the UV and optical data, we constrain directly the phase function of the dust.

While the phase function alone is a powerful datum on the nature of the dust, it alone is not sufficient to constrain the ratio of scattering efficiencies $Q_{\rm scat}$ in the UV versus the optical. The latter quantity is also needed to determine the incident flux. We can measure the optical reflectivity of the same dust as

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that creating the UV echo by simply observing 50–120 days later, the delay between shock breakout and the later maximum light peak in the optical. The optical echo flux can then be compared with the well-observed incident flux from SN 1987A itself. To derive the incident UV flux from these data, we need the UV/optical reflectivity ratio.

We are fortunate that for at least the outer ring of the interstellar echoes (at 1040 lt-yr) we can identify the echo nebulosity (Crotts 1988) as part of the N157C superbubble complex surrounding the stellar association LH 90 (cf. Lucke & Hodges 1970; Lortet & Testor 1984). It is likely that the flux incident on this nebula is dominated in the long term by LH 90 itself, the flux from which we can measure directly with UIT (and in the optical from the ground). Thus we can measure the UV/optical reflectivity ratio directly at given phase angle (unfortunately not in the range of α found above, but for $45^{\circ} \lesssim \alpha \lesssim 135^{\circ}$) by simply comparing the direct flux from LH 90 in the UV and optical to those found for reflection from a patch of N157C. We would anticipate that these results plus the phase function data at $\alpha = 4^{\circ}\!.9$ and $7^{\circ}\!.9$ might be sufficient to constrain the UV/optical reflectivity at these small angles. What we will actually find, however, is that the detection level of the data over the background flux is insufficient to complete this program. We will show, however, that a differential measurement between the current data and those from a future epoch might allow a much better determination.

A detection of the ultraviolet echo of SN 1987A has been reported (Panagia & Gilmozzi 1991) from data obtained with the *International Ultraviolet Explorer* (*IUE*). Unfortunately, these data involve a single small region of echo at a single epoch, so cannot serve in themselves to determine the incident flux. Nevertheless, they serve as an independent check on the reflected flux, which we will compare with our results.

2. OBSERVATIONS

Several exposures were taken of the region including SN 1987A and the echoes (the UIT field of view being 40′ across) on the STS 35 *Astro-1* mission. The longest of these exposures (1277 s) was obtained on 18:17 UT 1990 December 7 in the B5 filter band (which peaks at 1517 Å, with 50% power points at 1475 and 1716 Å, and 10% points at 1455 and 1822 Å). The longest exposure during orbital night was obtained on 10:09 UT 1990 December 7, was 200 s long, and was in the B1 filter band (which peaks at 1443 Å, with 50% power points at 1319 and 1706 Å and 10% points at 1289 and 1831 Å). Except where noted, we discuss only the data obtained in the B5 band.

Optical wavelength observations were obtained on the 0.9 m telescope at Cerro Tololo Inter-American Observatory. Images were obtained with a Tektronics 1024^2 CCD detector binned 2×2 to $0''.768$ pixel^{-1} resolution in typically $1''.5$ FWHM seeing. The filter used was a 145 Å–wide band centered at 6120 Å which suppresses nebular emission lines in the interstellar medium (cf. Crotts 1991). The most sensitive data, used here, were obtained on 1991 April 1, 116 days after the UIT exposures. These data were also supplemented by others (in *UBVRI*) from the Cerro Tololo Inter-American Observatory's SN 1987A data archive, in particular those taken on the same telescope on 1991 February 20 and March 7 and 20. The flux from stars and permanent reflection nebulosity was subtracted by comparing these data with earlier epochs' images of the same field, when the echoes had expanded to only smaller radii from the supernova. Except for the region around bright stars (affected by residuals of zero net flux due to improper subtraction in the stellar image profiles), the remaining flux in the regions of interest is due solely to the light echoes.

3. DATA REDUCTION AND RESULTS

To maximize the usefulness of the data for detecting a possible UV echo, we use an "optimal" or variance-weighted summation (Horne 1986) of pixel values in the UIT images. The weighting function $W = P^2/\sigma^2$, where P is a "profile" function describing the expected fractional contribution to the flux from that pixel relative to the total. Since we have optical echo fluxes from the same dust, as measured 116 days later in the light curve, we can use these to calculate P, assuming that the dust composition is uniform. The variance σ^2 is uniform in the UIT data (to within at most 20%, except near bright stars), so we include it as a constant factor.

To excise bright stars from both the optical and the UV data, we track the point-spread function of each star until it falls within a factor of 2 of the local background, then exclude a region around the star that extends 50% farther in radius. We also exclude regions that do not fall in the area $-90^{\circ} < \mathrm{P.A.} < 76^{\circ}$ between radii in the range $96'' < r < 127''$ for the outer strong interstellar echo, and $-90^{\circ} < \mathrm{P.A.} < 85^{\circ}$ between radii in the range $44'' < r < 127''$ for the inner one. These are by far the brightest regions echoing in the optical in 1991 April.

The resulting summation covers 7525 arcsec^2 of sky and results in a signal which is 9.4% higher than the background consisting of the mode of pixel values (of which about 1.1×10^{-17} ergs s^{-1} cm^{-2} Å^{-1} arcsec^{-2} remains after subtraction of instrumental and estimated airglow contributions) in the region $27'' < r < 127''$ and $-90^{\circ} < \mathrm{P.A.} < 90^{\circ}$. These values suggest that we must be most concerned with systematic errors due to background variation (especially since error due to count statistics over the echo region amounts to less than 3×10^{-3} of the background). By taking this same range in radius for the background and slicing into 20° sectors in position angle, one finds the mode varying over a range corresponding to surface brightnesses $0.8 \times 10^{-17} < f/\Omega < 1.2 \times 10^{-17}$ ergs s^{-1} cm^{-2} Å^{-1} arcsec^{-2} (neglecting a large uncertainty due to the subtraction of the estimated airglow contribution). Thus the surface brightness found for the echo, 3.0×10^{-18} ergs s^{-1} cm^{-2} Å^{-1} arcsec^{-2}, is only a factor of 2 times higher above the mean surface brightness than the brightest fluctuation in the background itself. This signal is difficult to perceive by eye in the UIT data; we can only note that the brightest patch in the UIT data that lands within our 7525 arcsec^2 region is also the brightest region in the 1991 April optical echoes, covering $285^{\circ} < \mathrm{P.A.} < 340^{\circ}$ in the outer echo.

4. DISCUSSION

We can compare this result with that from the only other report of an echo flux detection in the vacuum ultraviolet (Panagia & Gilmozzi 1991). Their result amounts to a surface brightness of 1.0×10^{-17} ergs s^{-1} cm^{-2} Å^{-1} arcsec^{-2}. (This is not what is inferred from their Fig. 2, but it has been corrected for a scale error in the axis denoting flux per angular bin; R. Gilmozzi, private communication.) These results cannot be compared directly, since they must be scaled by the dust density in the respective clouds and by the phase function at the two slightly different scattering angles ($4^{\circ}\!.1$ for *IUE* and $5^{\circ}\!.4$ for a weighted average of the UIT data). We note that the background flux found by UIT is consistent with the *IUE* value (1.5×10^{-17} ergs s^{-1} cm^{-2} $Å^{-1}$ $arcsec^{-2}$). The *IUE* echo cloud was the brightest patch visible at the epoch of discovery of the interstellar echoes, for which we have photometry in Johnson-Morgan *BVRI* (Crotts 1988). To facilitate this intercomparison, we also obtained *R* photometry of the optical echoes in 1991 April and find that the cloud studied by *IUE* was 3.6 times brighter than the weighted-average surface brightness we observed in 1991 April. Even for a maximally forward-scattering dust particle [$g = 1$ in the Henyey-Greenstein 1941 phase function $F(\alpha) = (1 - g^2)(1 + g^2 - 2g \cos \alpha)^{-3/2}$], the correction for the phase function between the two epochs' geometries is about a factor of 2.3, whereas a more realistic value of $g = 0.8$ produces a minor correction of 9.5%, and an even smaller correction if the optical wavelength g is greater than zero. If this factor (which would tend to enhance the cloud observed by *IUE* over that observed by UIT) is neglected, the surface brightness (*IUE*/UIT) in the UV of 3.3 is consistent with the ratio of surface brightnesses for the same clouds in the optical, 3.6. Panagia & Gilmozzi (1991) mention that the spectrum of the echo appears "hot" even in the 1250–1850 Å band of their data; this might be another factor allowing them to observe somewhat more flux than in the redder UIT bandpass. Unfortunately, the shorter wavelength band exposure on UIT is of insufficient duration to allow us to check this.

While with these data we have succeeded in measuring a flux and apparently confirming the measurement made with *IUE*, we have not succeeded in determining the reflectivity of the dust. As a consequence, we must depend on theoretical models to provide this information. We find that flux predictions constructed by various models tend to be consistent in the spectral range covered by our observations, e.g., the Woosley (1988) 10L model for shock breakout flux, which predicts a total fluence of 0.0045 ergs cm^{-2} $Å^{-1}$ at Earth, compared with the Shigeyama, Nomoto, & Hashimoto (1988) 11e1y6 model, which predicts fluence within 2% of the same value. These imply an incident UV/optical(6120 Å) fluence ratio 3.1, which can be compared directly with the observed echo UV/optical surface brightness ratio of ≈ 2 [weighted average surface brightness at 6120 Å = $(1.7 \pm 0.2) \times 10^{-18}$ ergs s^{-1} cm^{-2} $Å^{-1}$ $arcsec^{-2}$], implying a ratio in UV/optical reflectivity ratio ≈ 1. This is difficult to arrange for any grain that is also in the Rayleigh regime in the optical. One finds either that the scattering efficiency $Q_{\rm scat}$ is very much lower in the optical or that the narrow-angle phase function is much higher in the UV (cf. Wickramasinghe 1973). Either an optical wavelength λ^{-4} reflectance law does not apply to these clouds, or the UV burst was much weaker in total fluence than predicted.

5. CONCLUSIONS

Our result, while marginal, tends to confirm the result obtained by *IUE* (under very difficult observing conditions; Gilmozzi & Panagia 1991). Even taking our "detection" as an upper limit, this puts important constraints on the strength of the UV flux from shock breakout. Even with scattering no stronger in the UV than in the optical, the breakout flux in the 10 eV range cannot be stronger than that predicted by models (e.g., Woosley 1988, 10L model; Shigeyama et al. 1988, 11e1y6 model). This is an important check on our understanding of the early development of supernovae and their influence on their immediate surroundings by radiative ionization.

In addition, as we have found for the optical echoes, our data could be much improved by subtracting the background obtained from data of an epoch before or after the echoes propagated into the region of concern (Crotts 1992). This will hold for the UIT images as well. In principle, the UIT data in hand have more than enough signal versus shot noise to show the echoes clearly. Indeed, the signal obtained by *IUE* appears convincing only after the background is subtracted. This would seem even more promising in the case of UIT, with its wide field of view and much greater spatial information capability. As of this writing, UIT is scheduled to fly again in the next few years, opening the prospect for a much more accurate determination of the flux from the shock breakout of SN 1987A, as well as the scattering properties of dust in the ultraviolet.

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REFERENCES

Arnett, W. D. 1988, ApJ, 331, 377
Chevalier, R. A., & Emmering, R. T. 1988, ApJ, 331, L108
Chevalier, R. A., & Fransson, C. 1987, Nature, 328, 44
Crotts, A. P. S. 1988, ApJ, 333, L51
———. 1991, in SN 1987A and Other Supernovae, ed. I. Danziger & K. Kjar (Munich: ESO), 559
———. 1992, in preparation
Gouiffes, C., et al. 1988, A&A, 198, L9
Henyey, L. G., & Greenstein, J. L. 1941, ApJ, 93, 70
Horne, K. D. 1986, PASP, 98, 609
Lortet, M. C., & Testor, G. 1984, A&A, 139, 330
Lucke, P. B., & Hodges, P. W. 1970, AJ, 75, 171
Panagia, N., & Gilmozzi, R. 1991, in SN 1987A and Other Supernovae, ed. I. Danziger & K. Kjar (Munich: ESO), 575
Perrine, C. D. 1902, ApJ, 17, 310
Ritchey, G. W. 1902, ApJ, 15, 129
Shigeyama, T., Nomoto, K., & Hashimoto, M. 1988, A&A, 196, 141
Suntzeff, N. B., Heathcote, S. R., Weller, W. G., Caldwell, N., Huchra, J. P., Olowin, R. P., & Chambers, K. C. 1988, Nature, 334, 135
Wickramasinghe, N. C. 1973, Light Scattering Functions for Small Particles (New York: Wiley)
Witt, A. N., Stecher, T. P., Bohlin, R. C., & Petersohn, J. K. 1991, BAAS, 23, 882
Woosley, S. E. 1988, ApJ, 330, 218