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ORIGINAL ARTICLE

The *Swift* Ultra-Violet/Optical Telescope: a view of today and tomorrow

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Abstract Currently there are four operating near-UV imaging space telescopes, one of which is the *Swift* Ultra-Violet/Optical Telescope (UVOT). Although the UVOT was primarily built for observations of γ-ray bursts, it has become a powerful instrument for studying other types of UV and optical astronomical phenomena. Here we discuss the properties of the UVOT, summarize some of the science undertaken with the UVOT, and present other possible science goals for the UVOT that have not yet been pursued. We also discuss some lessons learned that apply to future UV telescopes.

Keywords Space vehicles: instruments · Ultraviolet: general · Gamma rays: bursts

1 Introduction

There are currently four operating near-UV imaging telescopes: *HST*–Wide-Field Planetary Camera 2 (WFPC2), *XMM*–Optical Monitor (OM; Mason et al. 2001), *Galaxy Evolution Explorer* (GALEX; Siegmund et al. 2004; Bianchi 2000), and *Swift*–Ultraviolet Optical Telescope (UVOT; Roming et al. 2005). A comparison of the four instruments reveals that the WFPC2 has the highest spatial resolution and sensitivity but the smallest field-of-view (FOV) while GALEX has the lowest spatial resolution and the largest FOV. Both WFPC2 and GALEX cover a bluer portion of the spectrum than UVOT or OM. The OM and UVOT are very similar telescopes with OM having a higher spatial resolution than UVOT while UVOT has a higher throughput ($\sim$10×), particularly in the bluest wavelengths, than OM. Of the four telescopes, UVOT has the fastest response for making observations and is therefore ideal for observing transient sources.

In this paper we focus on the UVOT. In Sect. 2, we briefly describe the characteristics of the UVOT. In Sect. 3, we review some of the science performed with the UVOT to date and summarize several potential science projects that can be performed. In Sect. 4, we discuss a few lessons learned from our experience that are applicable to future generations of UV telescopes.

2 UVOT characteristics

The UVOT has a 30 cm aperture, an f-number of 12.7 after the secondary mirror, and is of a modified Ritchey-Chrétien design. The detector is a micro-channel-plate intensified CCD and operates in a photon counting mode. By using a centroiding algorithm, the 256 × 256 pixel CCD is sub-sampled to a 2048 × 2048 pixel array, providing a scale of $0.5''$ per pixel and a FOV of $17'$ on a side. The wavelength response of the UVOT is 160–800 nm (Poole et al. 2008) with a $\sim 2''$ FWHM telescope PSF and a sensitivity of $\sim$21 mag in 1000 s, assuming a γ-ray burst (GRB) spectrum. A filter wheel containing eleven filters—three UV and three optical color filters, a clear (*white*) filter, an optical and

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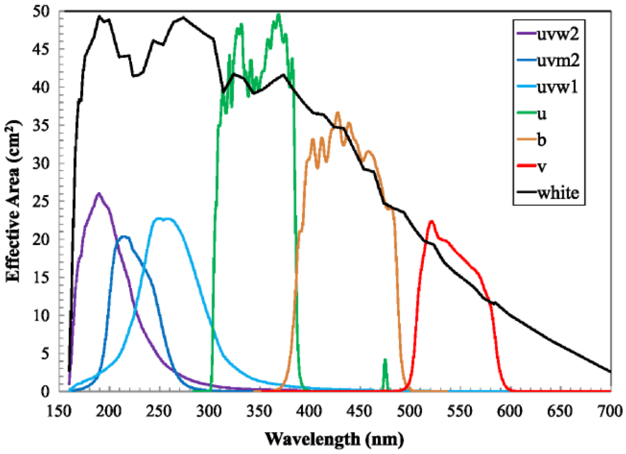

Fig. 1 The effective area of the UVOT filters

UV low-resolution grism, a field magnifier, and a blocking filter—is positioned before the detector. The response of the color and *white* filters can be found in Fig. 1. The UVOT is coaligned with the 15–150 keV Burst Alert Telescope (BAT; Barthelmy et al. 2005) and the 0.2–10 keV X-Ray Telescope (XRT; Burrows et al. 2005). A complete discussion of the UVOT is found elsewhere (Roming et al. 2005).

3 UVOT science

The UVOT is currently investigating the science associated with a number of different types of objects. A discussion of these assorted science cases is beyond the scope of this paper. Here we briefly outline the current science being performed with the UVOT, provide a more detailed discussion of a specific science case, and briefly discuss a few possible future science goals for the UVOT.

3.1 Current science investigations

The primary science for the UVOT, and the *Swift* mission (Gehrels et al. 2004) in general, is the characterization of GRBs and their afterglows. The UV/optical light curves produced by the UVOT has helped unravel the physics behind long GRBs (cf. Still et al. 2005; Blustin et al. 2006a; Grupe et al. 2007), short GRBs (cf. Roming et al. 2006b), X-ray flashes (cf. Schady et al. 2006), the so called "dark" bursts (cf. Roming et al. 2006a), the elusive GRB-supernovae connection (cf. Campana et al. 2006), and optical flares (cf. Roming et al. 2006c).

In addition to GRBs, the UVOT has been a pioneer in studying the UV properties of Type Ia (Brown et al. 2005; Immler et al. 2006) and Type II supernovae (Brown et al. 2007; Immler et al. 2007). Other investigations include multiwavelength outburst studies of black hole X-ray transients (cf. Brocksopp et al. 2006), high spatial resolution mapping of extinction in the SMC (cf. Blustin et al. 2006b), UV properties of comets (cf. Mason et al. 2007), and emission models for blazars (cf. Tramacere et al. 2007).

3.2 A specific science case: star formation

The UVOT is a particularly powerful tool for studying star-formation in nearby galaxies. We have obtained deep near-UV images in 3 filters (uvw2, uvm2, and uvw1) of a number of nearby galaxies. Compared to GALEX, our data provide improved color resolution in the near UV as well as improved spatial resolution ($\sim 2''$ vs. $5''$). Such data can be used in combination with optical observations to place constraints on the ages, masses, and reddening of star-forming regions in nearby galaxies and to study the star formation histories of these galaxies.

The first galaxy studied in this on-going *Swift* team project is M51. Figure 2 (left side) shows a uvw1 image of M51 with the location of star clusters indicated. Detection of the star clusters was performed by using a ring median filter to smooth the galaxy light and subtracting the galaxy continuum from the image. *SExtractor* was used to detect the star clusters, and photometry was performed using $6''$ apertures. Figure 2 (right side) shows a color-color diagram of the star clusters in M51, along with the evolutionary track of a solar-metallicity instantaneous burst, simple stellar population (SSP) model (Bruzual and Charlot 2003). The implied ages of the star clusters in M51 are young, ~ 3–5×10^8 years. We have not yet considered the effects of varying metallicity or reddening.

Since there are only broad-band UV detections, with no spectroscopic information in our sample, we can not directly identify HII regions in the galaxy. However, many of the HII regions in M51 have already been identified and published in the literature (e.g. Petit et al. 1996; Kennicutt 1988; Hodge and Kennicutt 1983; Carranza et al. 1969). A correlation of the star clusters found by UVOT to the previously published HII regions is planned for a future paper (Hoversten et al., in prep.).

3.3 Future science goals

One of the unique advantages of the UVOT over other UV telescopes is its rapid slewing capability and co-location with an X-ray and hard X-ray instrument. Due to these exceptional capabilities, the UVOT is ideal for performing a survey of nearby bright AGNs. The simultaneous observations by the UVOT, XRT, and BAT provide a spectral energy distribution over ~ 5 decades in energy. This would allow a step forward in our understanding of the processes underpinning the energy release in AGN (jets vs. disks). To date, multiwavelength simultaneous observations have only been possible for a tiny minority of sources (cf. Clavel et al.

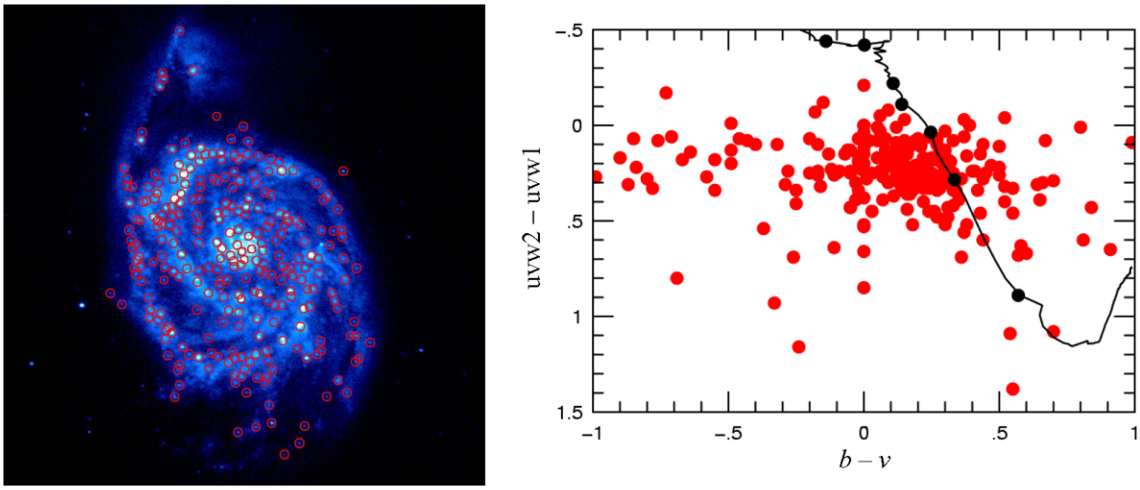

Fig. 2 *Left side:* uvw1 image of M51 with locations of star clusters indicated by *red circles*. There are 265 sources which include only those objects detected in all 3 UV filters. *Right side:* color-color diagrams for star clusters in M51. The *solid black curve* shows the intrinsic colors (no reddening) for a solar metallicity SSP model with a Salpeter IMF. The *black circles* mark ages (in log years) of 6.7, 6.9, 8.0, 8.3, 8.5, 8.7, and 9.0

1992). The addition of UVOT's timing capability (the telescope counts photons with a resolution of 11 ms) also enables a more complete exploration of the physics behind magnetic and non-magnetic CVs. The UV portion of the spectrum is particularly interesting in that it is a relatively new area to be surveyed.

Because the UVOT points in many random directions on the sky—200 square degrees in 2.5 years—it is also an ideal instrument for creating UV catalogs. Potential catalogs include: UV galaxy count (i.e. statistics of starburst galaxies), catalog of variable UV sources (cf. Welsh et al. 2005), database of nearby galaxies, catalog of serendipitous UV sources, and mapping the UV background (cf. Murthy and Henry 1995). The database of nearby galaxies can also further studies of UV extinction begun with GALEX (cf. Treyer et al. 2007). The advantage UVOT has over GALEX for such a study is its better spatial resolution and its less strict bright star constraints, i.e. the Magellanic clouds and the galactic plane are available.

Due to the UVOT's sensitivity (particularly in the UV) and photon counting capability, the UVOT is a good tool for providing faint UV standards. Some of the new and future UV telescopes are photon counting instruments that are more sensitive to fainter magnitudes than many of their predecessors. It has been recognized for many years the necessity for faint UV standards in order to calibrate these sensitive UV telescopes. However, no such standards have been clearly established. By combining Sloan Digital Sky Survey spectra of DA White Dwarfs with UVOT photometry, and comparing the spectroscopic and photometric data with models of pure hydrogen atmospheres in local thermodynamic equilibrium (LTE) and non-LTE, fainter UV standards can be established.

4 Lessons learned

With the forthcoming arrival of more sensitive UV photon counting detectors, such as *HST*'s Cosmic Origins Spectrograph, ASTROSAT's Ultraviolet Imaging Telescope, and the Tel Aviv University UV Explorer (TAUVEX), as well as the 1.7 m World Space Observatory and the planned HORUS telescope, an examination of the lessons learned from UVOT is a valuable process for improving the next generation of UV instruments. Here we briefly discuss three lessons learned.

The first and most important lesson learned, particularly for a UV instrument, is the criticality of molecular (which includes the careful selection of materials) and particulate contamination control. For the duration of the instrument design, integration, and test phases of the UVOT, a budget of 90 Å and Level 425 for the molecular and particulate contamination, respectively, was levied on the instrument. At the conclusion of instrument integration and test, the realistic deposition was 6 Å and <Level 300 for the molecular and particulate contamination, respectively. A comparison of the UVOT and OM is a good illustration of the importance of this tight contamination control.

The UVOT and OM have very similar designs, with the UVOT benefiting from the heritage of OM. The OM has a bonding material (Scotch Weld 1838) used around the optics that was later discovered to be a UV contaminant. This bonding material was the most probable, although not conclusive, cause of the ∼10× decrease in the OM transmission at the bluest wavelengths (see Fig. 3).

The second lesson learned is the necessity for creating UV filters with transmission profiles similar to the optical.

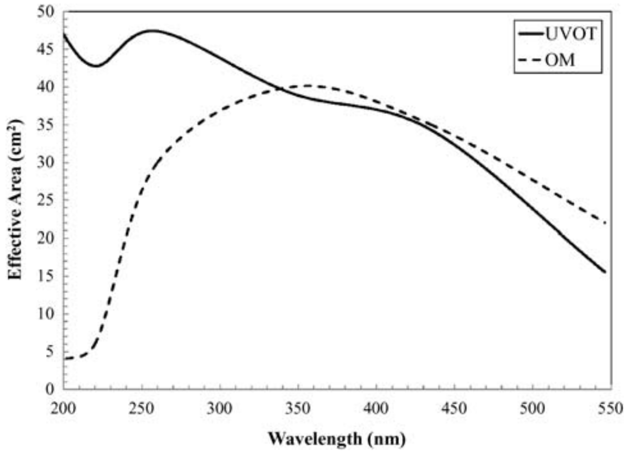

Fig. 3 A comparison of the UVOT and OM responses. The responses have been smoothed for both systems by taking the values at 193, 220, 260, 345, 435, and 546 nm, and interpolating between values

Most Johnson-like optical filters have rise-over-run transmission profiles (RORTPs) of ∼3 on either side of the filter's central wavelength. UV filters tend to have RORTPs of ∼0.2 which means that they have large tails in their transmission curves that allow optical light to contaminate UV science. This effect is most prominent for red objects, such as Type Ia supernovae, M-class stars, moderately extincted objects, etc. Without correcting for this effect, distinguishing between the optical and UV science is difficult.

The third lesson learned is the need for sensitive photon counting instruments with high temporal resolution. Timing studies are becoming more and more important (cf. Sect. 3.3). Faster space-based processors and memory are more readily available thus making timing studies much more accessible than in the past. If telemetry constraints prohibit all photon data being transfered to the ground, images can easily be created on instrument and then transfered to the ground.

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Facilities: Swift (UVOT).

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