

# Calibration of the *HST* ACS/WFC Linear Polarization Filters

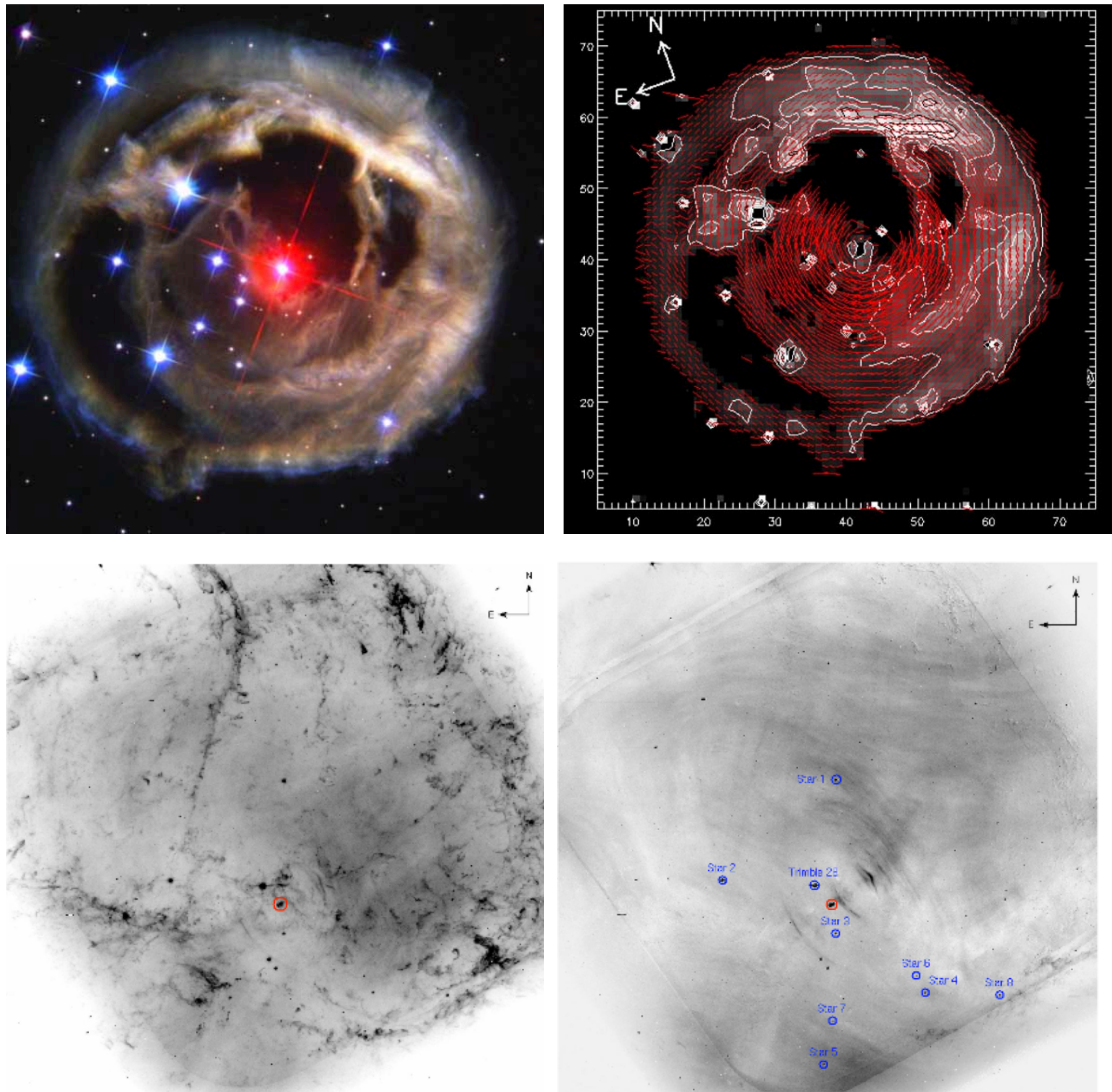
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We present the calibration of the *Hubble Space Telescope* (*HST*) linear polarization filters for the Advanced Camera for Surveys Wide Field Channel (ACS/WFC). Using observations of the bright ( $V \sim 11.7$  mag), unpolarized white dwarf G191-B2B and a polarized standard Vela 1-81 ( $V \sim 13.4$  mag), we re-estimate the coefficients required for transforming ACS/WFC images using the POL0V, POL60V, and POL120V filters into Stokes  $I$ ,  $Q$ , and  $U$  images, along with extracting the polarization fraction and angle. We further discuss the science use-cases for the ACS polarization filters in the era of joint *HST* and *James Webb Space Telescope* observations.

## Introduction

The ACS instrument on *HST* was installed in March 2002, and repaired during Servicing Mission 4 in May 2009. The ACS/WFC detector continues to operate and, among other modes, provides wide-field optical imaging with both the highest throughput for visible light on *HST* and also the largest field of view of all *HST* cameras. Among the active *HST* instruments, ACS also possesses the unique capability to detect **linear polarization** of light using a suite of polaroid filters. ACS polarization studies have had a wide range of application in the past including studies of synchrotron jets, light echoes, pulsar wind nebulae, comets, and the surface of Mars (see Figure 1).



**Figure 1:** Examples of ACS polarimetry from the literature.

*Top:* The V838 Mon light echo in December 2002 (Image credit: NASA, ESA, and the Hubble Heritage team. Science credit: Sparks et al. 2008). The left image is a false color image in F435W, F606W, and F814W. The right image shows the electric field vectors from the ACS polarization data.

*Bottom:* The Crab Nebula and pulsar. The left image shows the F606W + POLV0 data with the pulsar marked in red. The right image is an image representation of the polarization fraction derived from the ACS polarization data with the pulsar once again indicated in red. (Credit: Moran, P. et al. 2013)

## Linear polarization and ACS

Linear polarization of light occurs when the electric field vector of incident light is confined to a single plane. The two sets of polaroid filters in ACS (POLUV and POLV for ultraviolet and visible, respectively) can measure the fraction of light that is linearly polarized and the position angle of the electric field vector. Each set of polaroid filters accomplishes this by measuring the count rate of photons with electric field position angles at  $60^\circ$  rotations with respect to each other. Thus, there is a POL0V filter and also POL60V and POL120V that correspond to  $60^\circ$  and  $120^\circ$  rotations, respectively, to the POL0V filter (and likewise for the UV filters). These filters are typically crossed with the spectral filter of choice (e.g., F606W). The UV polarizers are Filter Wheel 1, and thus may be crossed with the F435W and F814W filters (however, the latter is inadvisable). The visible polarizers are on Filter Wheel 2, and can be crossed with the remaining WFC filters.

Stokes Parameters

$$I = \left(\frac{2}{3}\right) (C_0 r_0 + C_{60} r_{60} + C_{120} r_{120})$$
$$Q = \left(\frac{2}{3}\right) (2C_0 r_0 - C_{60} r_{60} - C_{120} r_{120})$$
$$U = \left(\frac{2}{\sqrt{3}}\right) (C_{60} r_{60} - C_{120} r_{120})$$

Derived Values

$$P = \frac{\sqrt{Q^2 + U^2}}{I} \times \left(\frac{T_{\text{par}} + T_{\text{perp}}}{T_{\text{par}} - T_{\text{perp}}}\right)$$
$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{U}{Q}\right) + (\text{PA\_V3}) + \chi$$

From the count rates, we can determine the Stokes parameters  $I$ ,  $Q$ , and  $U$  using the equations above (Lucas et al. 2018). In these equations, the numbered subscripts indicate polaroid filter,  $r$  is the count rate in electrons per second, and  $C$  is a calibration term that must be applied to each filter. Using the Stokes parameters, we can also derive the polarization fraction ( $P$ ) and the position angle of the electric field vector ( $\theta$ ). In these equations,  $T_{\text{par}}$  and  $T_{\text{perp}}$  refer to the parallel and perpendicular throughput, respectively, while PA\_V3 is the roll angle of the telescope along the V3 axis, and  $\chi$  is a constant for the WFC detector.

## Calibration of the Polarizers

We calibrate the polarizers using observations of two standard stars: one unpolarized (G191B2B; a white dwarf), the other having 6 – 7% polarization (Vela 1-81; an OB star). We observed Vela 1-81 at three roll angles in F475W and F775W, and at one roll angle for F606W. As our reference for the calibration, we use ground-based polarimetry in the Johnson filters from Whittet et al. (1992; see Table 1). New observations come from *HST* programs 13964 and 14407 (PI: McMaster).

Filter	$P$ (%)	$\theta$ (deg.)
Johnson $B$	$6.10 \pm 0.30$	$1 \pm 1$
Johnson $V$	$6.86 \pm 0.13$	$1 \pm 3$
Johnson $R$	$6.85 \pm 0.19$	$1 \pm 1$
Johnson $I$	$6.29 \pm 0.10$	$179 \pm 1$

**Table 1:** Ground-based polarimetry measurements of Vela 1-81 (Whittet et al. 1992). Vela 1-81 is an OB star that serves as the polarized standard for ACS polarimetry calibration.

For the unpolarized star, we have observations at only one roll angle. We then compute the count rate ratios of POL60V/POL0V and POL120V/POL0V, which scale the count rates to force Stokes  $Q = U = 0$ . We do not scale for Stokes  $I$  at this time. Ideally, Stokes  $I$  is equal to the count rate without the polaroid filters in the light path. We use the count rate ratios from the unpolarized source to determine the properties of the polarized standard compared to the ground-based values as a check of our method.

Filter	Polarizer (normalized to POL0V)	Old Term	New Term	Vela $\langle P \rangle$ (%)	Vela $\langle \theta \rangle$ (deg.)
F475W	POL60V	0.972	0.976	$6.66 \pm 1.88$	$2.09 \pm 9.72$
	POL120V	1.001	1.015		
F606W <sup>†</sup>	POL60V	0.979	0.984	6.94	173.06
	POL120V	1.014	1.056		
F775W	POL60V	1.025	0.948	$5.58 \pm 1.30$	$179.71 \pm 0.94$
	POL120V	1.015	0.992		

<sup>†</sup> The F606W data of Vela 1-81 were taken at only one roll angle.

**Table 2:** ACS/WFC polarizer calibration coefficients. The “Old Term” column refers to the values from Biretta et al. (2004), while the “New Term” column uses data from this study. Using the new coefficients, we compute the average polarization fraction and position angle of Vela 1-81 from the new observations at different roll angles (note F606W has only one roll angle). Uncertainties represent the standard deviation.

## Conclusions:

- We find that the coefficients required to derive the Stokes parameters have changed since their last measurement in 2004.
- Testing the use of the pixel-based CTE correction for WFC data shows no difference in results to  $\sim 0.02\%$  in the polarization fraction, and in the coefficients at the level of  $\sim 0.001$ .
- The spread in the position angles for F475W is quite large, and at any roll angle the value of  $P$  and  $\theta$  did not match well compared to the ground measurements for both F475W and F775W. This may be indicative of the effects of birefringence and diattenuation described by Biretta et al. (2004).

## Future Work:

- Perform analysis for F435W with the POLUV filter set.
- Requested repeat observations of F775W to test if saturation affected the results.

## Joint *HST* + *JWST* Science

After the launch of *JWST*, there will be opportunities for joint observations with both missions. Here, we suggest some of the broad science categories that could benefit from combining *JWST* infrared data with ACS polarimetry.

- Dusty stellar winds of AGB and post-AGB stars
- Pre-planetary discs
- Interactions between comets and the Solar wind

## References

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