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Proxima Centauri: Time-resolved Astrometry of a Flare Site using *HST* Fine Guidance Sensor 3

G. Fritz Benedict[1], Barbara McArthur[1], E. Nelan[2], D. Story[1,3], A.L. Whipple[1,4], P.J. Shelus[1], W.H. Jefferys[5], P.D. Hemenway[6], Otto G. Franz[7], L.H. Wasserman[7], W. van Altena[8], and L.W. Fredrick[9]

Abstract:

While carrying out astrometric monitoring of Proxima Centauri (a known flare star, V 645 Cen) for planetary mass companions with *Hubble Space Telescope* Fine Guidance Sensor 3 (FGS 3), we obtained photometry and astrometry for several significant and several minor flare events. For one major flare that produced a $\Delta V \sim -0.6$, time-resolved astrometry (effective 1 Hz rate) indicates a detonation at a distance 5.2 ± 2.4 stellar radii from the center of Proxima Cen.

1. Introduction

We report on a serendipitous result, ancillary to a four year search for astrometric perturbations associated with Proxima Cen. In addition to establishing mass limits for possible planetary companions to Proxima Cen, (Benedict et al., 1997a) our observations with FGS 3, a two-axis interferometer aboard the *Hubble Space Telescope (HST)*, permit time-resolved photometry and astrometry at 1 Hz rates. Bradley et al. (1991) provide an overview of the FGS 3 instrument. Benedict et al. (1994) describe the astrometric capabilities of FGS 3. An assessment of its photometric qualities (Benedict et al. 1993) also provided the first evidence for periodic variability of Proxima Cen. This latter result was based on a one year time span. A paper exploring the periodic variations seen over four years is in preparation (Benedict 1997b). Here we discuss very short time-scale variations seen in the Proxima Cen photometry and astrometry. After the *HST* High Speed Photometer was removed during the 1993 Servicing Mission, FGS 3 remained the fastest photometer aboard.

We can detect flaring activity (Benedict et al. 1993). We can do millisecond of arc (mas) precision and accuracy astrometry (Franz et al. 1995). Here we demonstrate that for very bright, explosive flares the very short time-scale vari-

[1]McDonald Observatory, University of Texas
[2]Space Telescope Science Institute
[3]Now Jackson & Tull.
[4]Now Allied-Signal Aerospace.
[5]Astronomy Dept., University of Texas
[6]University of Rhode Island
[7]Lowell Observatory
[8]Astronomy Dept., Yale University
[9]Astronomy Dept., University of Virginia

ations seen in the Proxima Cen photometry are also evident in the astrometry. We can observe not only that such a flare occurs, but where it occurs relative to the photocenter of Proxima Cen. In this paper we adopt the following parameters for Proxima Cen: $M_V = 15.45 \pm 0.1$, $B-V = 1.94$, Sp. Type = M5Ve, $M_{\rm Proxima} = 0.11 M_\odot$ (Kirkpatrick & McCarthy 1994), $L_{\rm Proxima} = 0.001 L_\odot$ (Leibert & Probst 1987), and $R_{\rm Proxima} = 0.15 R_\odot$ (Panagi & Mathioudakis 1993). At a distance of 1.3 pc, the diameter of Proxima Cen is ~ 1 mas.

2. Observations

We discuss the data from which our flare observations are drawn, note long-term periodic variations; and identify flares.

2.1. Data

Our position and brightness measurements are comprised of series of 0.025 sec samples (e.g., 40 Hz data rate), of either ~80 or ~600 sec duration, the latter obtained within Continuous Viewing Zone (CVZ) orbits, during which our target was never occulted by the Earth. The filter used (F583W) has a bandpass centered on 583 nm, with 234 nm FWHM. The data now include over 146 short segments secured over 4 years (March 1992 to Apr. 1997) and 15 long segments (July 1995 to July 1996). Each orbit contains from two to four segments.

2.2. Long-Term Photometric Variations

The average photometry for each short or long (marked C for CVZ) exposure segment appears in Figure 1, plotted versus Modified Julian Date (MJD). For a 90 sec observation FGS 3 has a 1-σ precision of 0.001 magnitude at $V = 11$ (Benedict et al. 1993). The statistically significant period and amplitude variations will be discussed elsewhere (Benedict 1997b).

2.3. Flares

Exposures affected by flares are marked F in Figure 1. On average 10 minutes elapses between observations secured during each orbit.

• Flares on MJD 906 and 1164 are slow, relatively faint ($\Delta V < -0.10$), and multipeaked. See Benedict (1993) for a discussion of the MJD 906 flare. The MJD 1164 event rose very slowly, increasing through exposure 1 (+) to 3 (*).

• The flare on MJD 1368 rises slowly to maximum, with ($\Delta V \sim -0.17$), and is multipeaked, significantly perturbing the average V brightness. The final exposure (*) of this orbit is brighter than the second, possibly the tail-end of, or precursor to, another flare.

• The flare on MJD 1266 was very bright, but very brief, having only a small effect on the average magnitude derived from the 100 sec data segment. Exposure 3 (*) possibly detects the tail of the very bright flare. For now we concentrate on this explosive flare, since only it had detectable astrometric consequences.

3. Flare Astrometry

The explosive flare on MJD 1266 is the brightest flare detected during over six

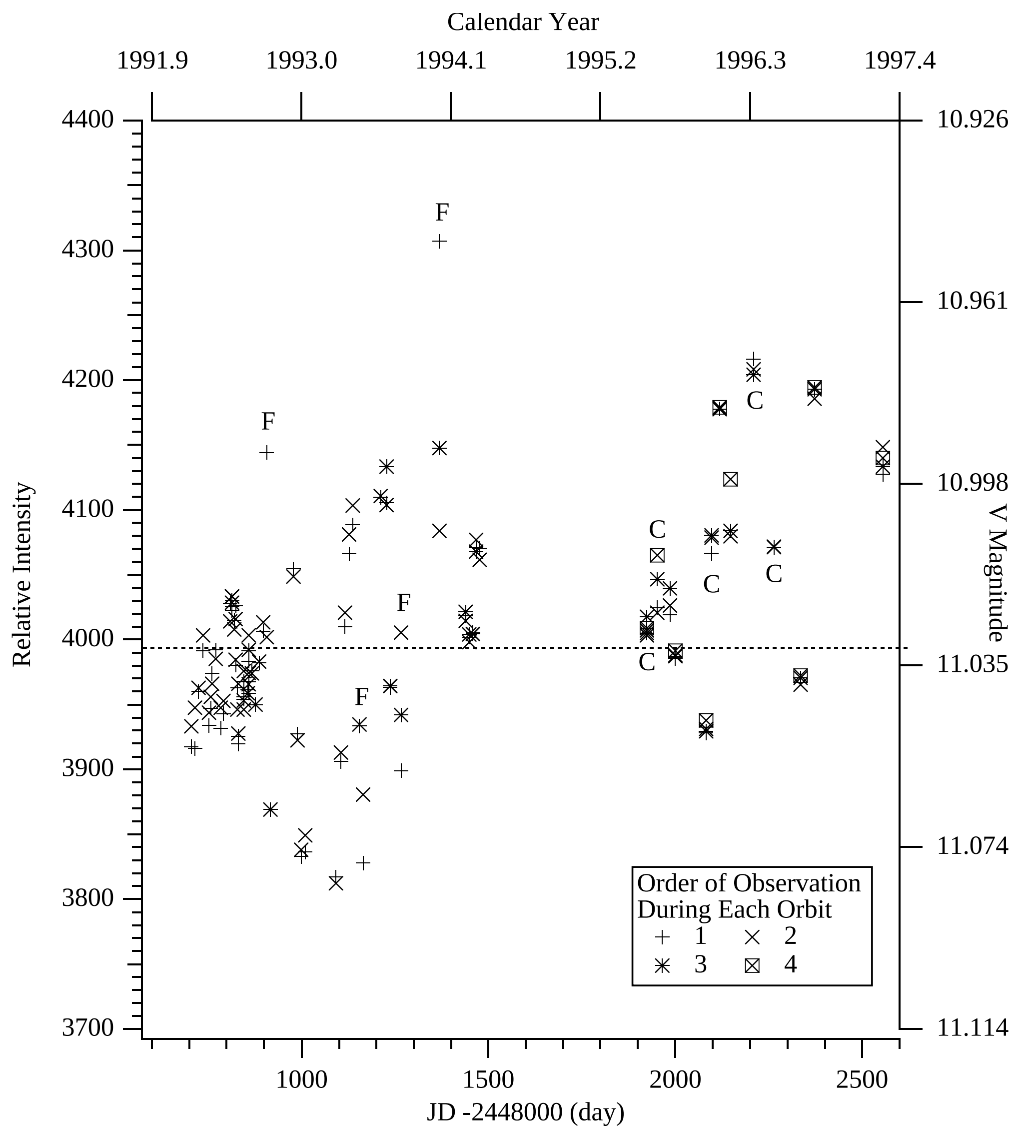

Figure 1. Photometry of Proxima Cen. Each symbol represents the average of a short or long (labeled C, for CVZ) exposure. Flares are marked F. Error bars are smaller than the plotted symbols. Each orbit contains 2, 3, or 4 exposures, either all short or all long.

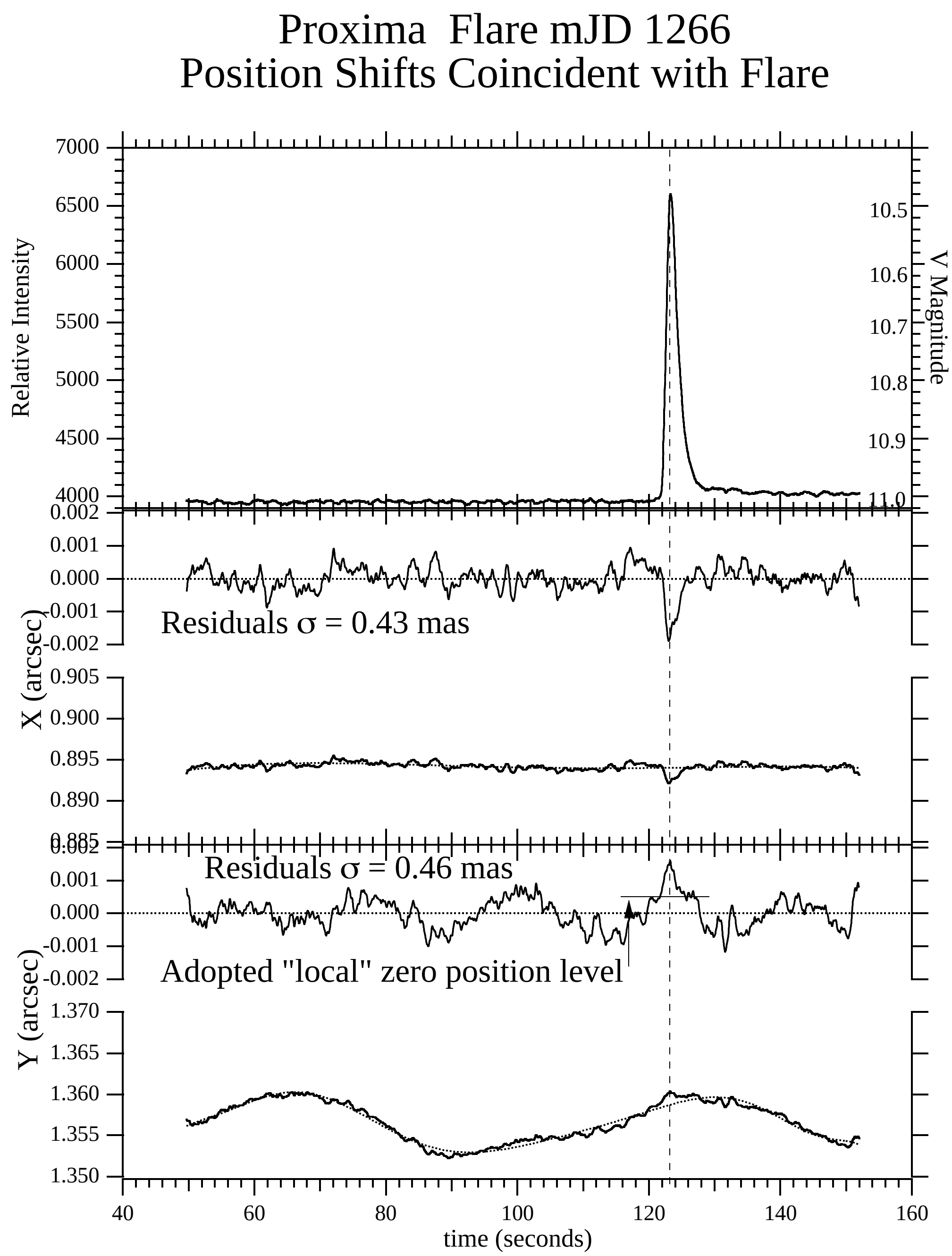

Figure 2. Explosive flare. Plotted against time in seconds, traces bottom to top are: y position and high-order polynomial fit, y position residual to polynomial fit, x position and polynomial fit, x residual, and the brightness of Proxima Cen. This particular short exposure had a 100 sec duration.

hours of on-target data acquisition. The MJD 1266 event prompted the scheduling of five Continuous Viewing Zone orbits from July 1995 to July 1996, each permitting 30 minutes of monitoring for flares (C in Figure 1). No significant flares were detected, an anticipated (but unwelcome) result, since very bright, explosive flares are relatively rare. One algorithm (Walker 1981) predicts a $\Delta V \sim -0.6$ magnitude flare once every 31 hours. This same algorithm predicts one $\Delta V \sim -0.05$ event every five hours. That we detected many more modest-sized events in 1993 may indicate that Proxima Cen was in a minimum of an activity cycle in 1995-96.

The top panel in Figure 2 shows the variations in brightness measured for Proxima Cen for the entire 100 sec data stream bracketing the flare. The photometric and positional data were acquired at a 40 Hz sampling rate. All plotted flare photometric and astrometric data have been boxcar averaged over 41 channels, producing an effective sampling rate of 1 Hz. The flare had a rise time of ~ 1.4 sec, a $\Delta V \sim -0.6$ magnitude, and was characterized by an exponential decay with $1/e$ time $= 0.71 \pm 0.01$ sec.

3.1. Removing Spacecraft Motion

The guiding system uses one FGS to control *HST* pitch and yaw (the dominant guide star), another FGS to control *HST* roll, while FGS 3 carries out astrometric programs. The time constants in this servo system permit high-frequency oscillations in the pointing. These solid-body motions are witnessed by all three FGS and can be removed from FGS 3 using the parallel position data streams from the guiding FGS's.

3.2. Removing Residual FGS 3 Motion

That this correction technique is less than perfect is easily seen in the center and bottom panels in Figure 2. Once the high-frequency solid-body *HST* motions have been removed, we find autonomous motions with amplitude 1-5 mas in FGS 3. (Millisecond of arc astrometry is obtained with FGS 3 by taking the median of 30 – 90 sec duration data streams for each observation.) Making the assumption that the motion of FGS 3 is smoothly varying, we remove it by fitting and subtracting a high-order polynomial. The residuals to this correction are positional jitter noise, characterized by gaussians with $\sigma \sim 0.45$ mas.

3.3. Flare-Induced Position Shifts

Our astrometry yields position shifts for Proxima Cen coincident with this flare (Figure 2). The shifts are unlikely a chance occurrence, since the return to the original, pre-flare x and y positions are exponential with the same time constant as the photometric decay (Figure 3).

From Figure 2 we measure (average over full width at 90% flare peak intensity) shifts $(x_s, y_s) = (-1.6 \pm 0.4, +0.7 \pm 0.5)$ mas. Consider an explosive, bright stellar flare associated with Proxima Cen. For a few seconds we have a bright blue star near a bright red star, e.g., a binary star. FGS 3 temporarily measures a position produced by a linear superposition of two interferometer response functions (Franz et al. 1991). At the peak of the flare, the observed position of Proxima Cen is a weighted (by intensity) average of the flare and star positions. Considering x only , we assume

$$I_f \cdot x_f = I_s \cdot x_s \tag{1}$$

where x_f and x_s are distances from the photocenter of the flare and star combination. We obtain x_s by measuring the shift seen in Figure 2. I_f and I_s are flare and quiescent Proxima Cen fluxes. Solving for x_f, we obtain $x_f + x_s$, the flare detonation distance from the pre-flare Proxima Cen photocenter.

3.4. The Lateral Color Effect — A Complication

Unfortunately, we cannot immediately interpret the shifts seen in Figure 2 as purely a perturbation in the position due to an off-center flare. We must first correct for the Lateral Color effect, a positional shift caused by refractive elements in each FGS (Bradley et al. 1991). The measured position of a star may depend on its color. The FGS 3 coordinate system has x along the long axis of the pickle-shaped detector-accessible area and y perpendicular to x. In this system a red star is displaced towards positive x relative to a blue star at the same location. We characterize this shift as a function of $B - V$ color,

$$\begin{aligned} x_c &= x_o + ctx \cdot (B{-}V), \\ y_c &= y_o + cty \cdot (B{-}V) \end{aligned} \tag{2}$$

where ctx and cty are the shift in mas produced by a change in color $\Delta B{-}V =$ 1.0. Two independent on-orbit measures of ctx and cty yield a weighted average

$$\begin{aligned} ctx &= 0.9 \pm 0.2, \\ cty &= 0.0 \pm 0.2 \end{aligned} \tag{3}$$

agreeing with a pre-launch ground-test. Measuring a pre-flare brightness $V =$ 11.02, the flux from the flare is equivalent to $V = 11.36$. Consider a flare detonation site in the center of the Proxima Cen disk $(x, y = 0, 0)$. From equation 2, and assuming an explosive flare color, $B{-}V = -0.1 \pm 0.2$ (Walker 1981), this flare and Proxima Cen ($B{-}V$= 1.94) would be separated by $x_f{+}x_s = -1.84{\pm}0.3$ mas, all in x. Such a detonation site would produce a photocenter shift $x_s = -0.8$ mas, due only to Lateral Color.

3.5. The Flare Location

From our observed shift, $x_s = -1.6$ mas, the relative star and flare brightnesses, and equation 1, we calculate an observed total separation $x_f + x_s = -3.8 \pm 1.0$ mas. Correcting each component for Lateral Color (equation 2, shifting Proxima Cen to negative x, the flare to positive x), we obtain $(x_f + x_s)_c = -2.0 \pm$ 1.0. There being no Lateral Color correction necessary for y, we simply apply equation 1 (with $y_s = 0.7$ mas) and derive $y_f + y_s = 1.7 \pm 0.7$ mas.

To produce the observed shift the flare detonated at a radial distance r = 2.6 ± 1.2 mas from the center of Proxima Cen. From the orientation of *HST* on that date, the flare occurred at p.a. $\sim 200\,^\circ$. With our assumed stellar diameter,

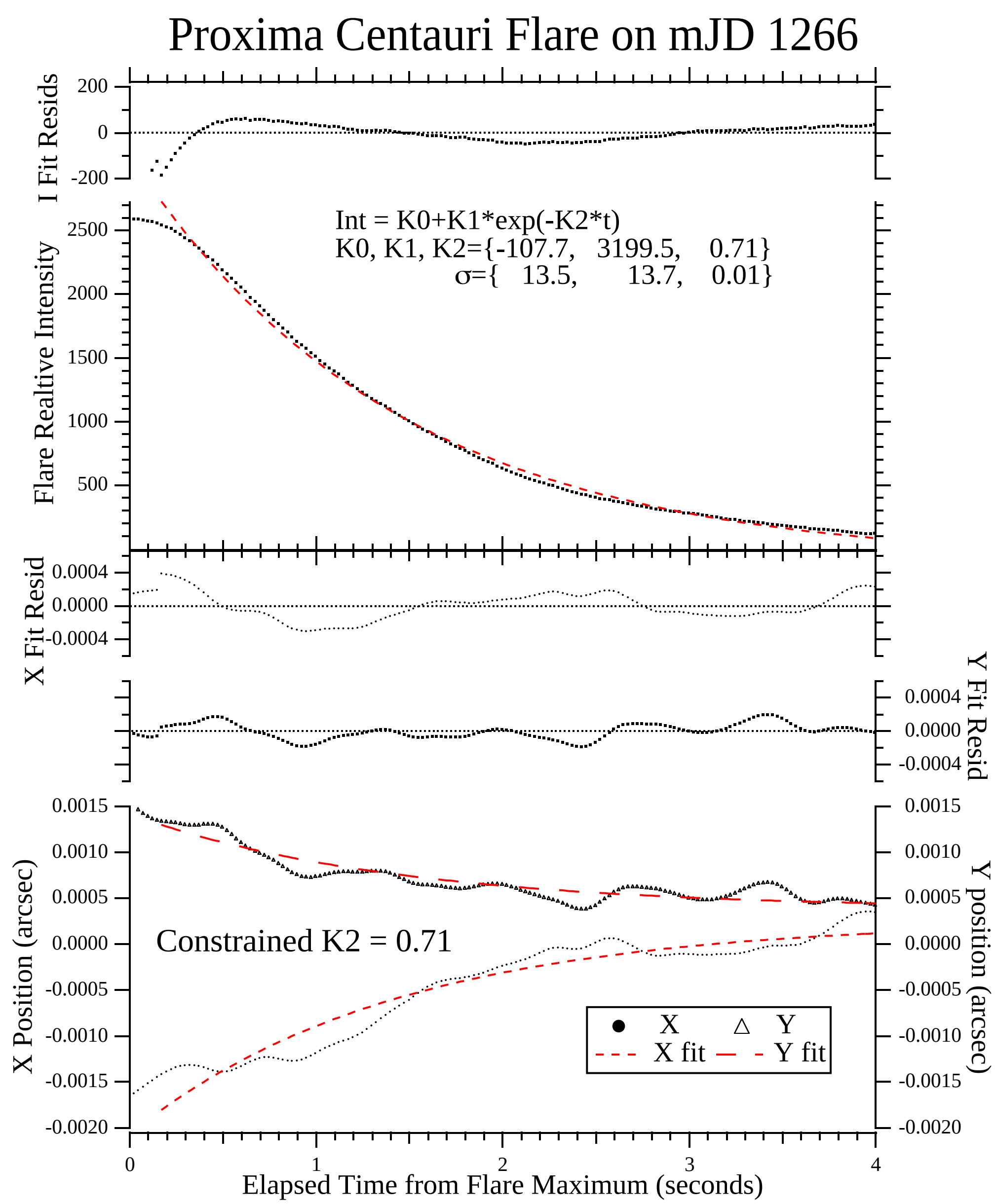

Figure 3. Flare-induced positional shifts. Photometric and astrometric changes revert to near pre-flare values with the same exponential time-constant.

the detonation occured 5.2 ± 2.4 stellar radii from the center of Proxima Cen. Considering y only (to ignore the larger but equally uncertain ctx Lateral Color correction), the flare detonated 3 ± 1 stellar radii from the center of Proxima Cen. These results seem to indicate that the detonation occurred well away from the limb of Proxima Cen.

4. Conclusions and Future Work

We have a marginal measurement ($\sim 2.5\sigma$) of the position of an explosive flare relative to the center of the stellar disk. Perhaps the primary value of our result lies in motivating future similar efforts with ground or other space-based interferometers.

It also serves as an example of a type of cosmic noise to be encountered when measuring positions of stars with precision far better than 1 millisecond of arc. The Keck Interferometer may have a measurement precision surpassing 50 microarcseconds. The Space Interferometry Mission (*SIM*) may achieve 2 microarcseconds (Shao 1995). At this precision flares associated with stars far more distant than Proxima Cen and flares far fainter than the subject of this note will become a source of irritation for some astrometrists, but a rich source of interesting astrophysics for others.

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