

**Interferometric Astrometry with *Hubble Space Telescope* Fine
Guidance Sensor 3:
The Parallax of the Cataclysmic Variable
TV Columbae**

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ABSTRACT

TV Columbae (TV Col) is a 13th magnitude Intermediate Polar (IP) Cataclysmic Variable (CV), with multiple periods found in the light curves. Past estimates predicted a distance of 400 parsec to greater than 500 parsec. Recently completed Hubble Space Telescope (HST) Fine Guidance Sensor (FGS) interferometric observations allow us to determine the first trigonometric parallax to TV Col. This determination puts the distance of TV Col at 368_{+17}^{-15} parsecs.

CD-32 2376, a 10th magnitude Tycho Catalog star, is a reference star in the TV Col frame. We find a distance of 127.7_{+1}^{-1} parsecs.

Subject headings: astrometry, stars: distances, stars: novae, cataclysmic variables

1. Introduction

Cataclysmic variables are binary systems consisting of a white dwarf (the primary) that receives mass from the Roche lobe of a low-mass, late-type companion (the secondary). If the white dwarf is strongly magnetized, the binary is categorized as a Magnetic Cataclysmic Variable (MCV). MCVs have two sub-classes depending upon the magnetic field strength: the Intermediate Polars (IP) (sometimes called DQ Hers) and the Polars (sometimes called AM Hers). In IPs, the transferred matter from the secondary moves through an accretion disk until the magnetic field of the white dwarf disrupts the disk and channels the flow along field lines onto the primary. X-rays are produced by the shock-heated gas near the surface of the white dwarf, while the UV and optical emission is mostly from the accretion disk. IPs rotate asynchronously, unlike Polars, due to their greater accretion rate and greater separation (Patterson, 1994), weaker magnetic fields on the primaries (Warner 1995), and the geometry of the magnetic field (Robinson, E. L, 2000, personal communication). IPs represent about 5-10% of all CVs, see Patterson(1994) and Warner(1995) for reviews of this class. Like most other CVs, distances are very uncertain for most of the IPs (Berriman, 1987).

TV Col, an IP star, was first discovered as the hard X-ray source 2A 0526-328 by Cooke et al.(1978). The X-ray source was optically identified with TV Col by Charles et al. (1979), being the first CV discovered by its X-ray emission. It has an orbital binary period of 5.486 hours (Hutchings et al., 1981) detected from the emission-line radial velocities. TV Col shows four additional periods: a 1911 s X-ray period representing the rotation period of the white dwarf - the spin period (Schrijver et al., 1985), a 4 day nodal precession of the accretion disc period (Hellier, 1993), a ~ 5.2 hour period which is the beat between the two longer periods (Motch, 1981) - a negative superhump (Retter & Hellier, 2000), and a photometric period of 6.36 hours (Retter & Hellier, 2000) - a positive superhump. It

has the longest orbital period of any permanent superhump system. TV Col has 0.1 mag rapid flickering (Barrett et al., 1988) and frequent, small-amplitude outbursts of luminosity (Szkody & Mateo, 1984, Cordova, 1995). TV Col also has had dwarf novae-like short outbursts of 4 magnitude amplitude, observed optically and with IUE (Hellier & Buckley, 1993; Hellier, 1993; Szkody & Mateo, 1984; Schwarz et al., 1988; and Schwarz & Heenskerk, 1987).

2. Observations and Reductions

The observations of TV Col (ICRS 2000: 05 29 25.57, -32 49 95.2) were made with Fine Guidance Sensor 3 (FGS3) on the HST. Astrometry with the HST Fine Guidance Sensors has been previously described (Benedict et al., 1994; Benedict et al., 1993), as has the FGS instrument (Bradley et al., 1991). Ten observations (one orbit each) of TV Col near maximum parallax factors were made between 1995 and 1998 with FGS3 in POS (fringe tracking) mode. HST FGS parallax observing strategies and reduction and analysis techniques have been described by McArthur et al. (1999), Benedict et al. (1999), Harrison et al. (1999), and van Altena et al. (1997).

FGS astrometry is relative to a local reference frame. To obtain an absolute parallax for our target requires estimates of the absolute parallaxes of the stars comprising our local reference frame. To obtain these estimates we require photometry and classification spectra. We obtain JHK photometry from the second incremental release of the Two Micron All Sky Survey (2MASS) catalog; B, V, and I from CCD observations (obtained at New Mexico State University); and Washington-DDO photometry from the University of Virginia. We obtain an upper limit on interstellar absorption in the direction of TV Col from the NASA/IPAC Extragalactic Database (NED) compilation of the Schlegel, Finkbeiner & Davis (1998) reddening estimates. This provides a color excess, $E(B - V)$, and through

the standard relationship, $A_V/E(B - V)=3.1$, an absorption value, A_V . The effects on the JHK colors are at or below 0.02 magnitude.

We obtained stellar classifications from two sources; the WIYN telescope² multiobject spectrograph (MOS/Hydra) and the CTIO 1.5m with Cassegrain spectrograph. The two independent estimates of spectral type and luminosity class are listed in Table 1.

The final adopted spectral types are the result of plotting the photometry (collected in Table 2) on several color-color diagrams ($B - V$ vs $V - K$ and $J - K$ vs $V - K$) upon which are impressed a mapping between colors and spectral types from Bessel & Brett (1988) and Allen’s Astrophysical Quantities 4th edition (Cox, 2000, hereafter AQ2000). Because both sources for our spectral types and luminosity classes expressed some doubt as to the luminosity class, we use Washington-DDO photometry (Majewski et al., 2000) to confirm their estimates. Plotting our reference stars on the giant/dwarf discrimination plane (M-D vs M-T₂, Figure 1), reference stars 1, 2, and 3 are clearly dwarfs. Ref-4 is borderline dwarf/giant or a metal poor dwarf. Because we obtain a better solution (the ratio of χ^2 to the number of degrees of freedom is smaller), we adopt a dwarf luminosity class for ref-4. V magnitude and colors are listed in Table 2.

Absolute magnitudes, M_V , are taken from the AQ2000 tables as a function of spectral type. We assume an error for each M_V consistent with the spectral type and luminosity class differences among WIYN, NMSU, and Washington-DDO photometry (Tables 1,2, 3). The resulting absorption-corrected distance moduli with errors and derived parallaxes are presented in Table 3. These are the parallaxes and associated errors used in the modelling. The spectrophotometric parallax of ref-1 and our derived value agree within the errors,

²The WIYN Observatory is a joint facility of the University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories.

providing confidence in our approach.

The average color of the reference stars and our science target differ, with $\Delta(B-V) \sim -0.91$. Therefore, we apply the differential correction for lateral color discussed in Benedict et al., 1999 to the TV Col observations. The GaussFit solved equation of condition for TV Col becomes:

$$x' = x + lc(B - V) \tag{1}$$

$$y' = y + lc(B - V) \tag{2}$$

$$\xi = A * x' + B * y' + C + R_x \times (x'^2 + y'^2) - \mu_x - P_\alpha \pi_x \tag{3}$$

$$\eta = -B * x' + A * y' + F + R_y \times (x'^2 + y'^2) - \mu_y - P_\delta \pi_y \tag{4}$$

where x and y are the rectangular HST coordinates, lc is the derived lateral color correction (Benedict et al., 1999); $B - V$ is the B-V magnitude; A and B are a set of scale plate constants, C and F are zero point corrections, R_x and R_y are radial terms, μ_x and μ_y are proper motions, P_α and P_δ are parallax factors, and π_x and π_y are the parallaxes in x and y. The spectrophotometrically determined parallaxes of the reference frame stars are modelled simultaneously as observations with errors to produce an absolute, not relative parallax for TV Col.

Comparing Tables 3 and 4 we find that the final adjusted absolute parallaxes for the reference stars agree with the spectrophotometric estimates within the errors. Our derived absolute parallax for TV Col is given in Table 5, along with a relative proper motion. As seen in Table 4, the standard errors resulting from the solutions of the equations for parallax and proper motion are sub-milliarcsecond. Figure 2 shows histograms of the the residuals from the fit of the target and the reference frame stars. The histogram of residuals is by far the best we have seen in dealing with over twenty FGS parallax data sets. Typical Gaussians fits are characterized by sigmas of order 1 mas. This was obviously an astrometrically very quiet reference frame. A generous well-characterized reference frame

surrounding the target along with exceptional instrument performance evidenced by the small standard error of the guider FGS’s contributed to the very low internal errors for these observations. Typical internal errors for FGS parallaxes range 0.3 - 0.7 mas. This 0.1 mas internal error is the luck of the draw. Our systematic errors in parallax determinations are likely larger.

3. Trigonometric Parallax and Absolute Magnitude of TV Col

Using the weighted spectrophotometric parallaxes of the reference frame, the simultaneous modelling of the observations gives an HST parallax for TV Col of 2.7 ± 0.11 mas, for a distance of 368_{+17}^{-15} parsecs (Table 5). The distance estimates from other non-astrometric methods are listed in Table 7.

The distance modulus ($-5 + 5 \log(1/\pi)$) for TV Col is 7.84. Using Bruch and Engel’s (1994) visual magnitude of 13.75 ± 0.1 for the apparent magnitude we obtain an absolute magnitude (M_V) of $5.92_{+0.1}^{-0.1}$. Adjusting the distance modulus with a correction for A_v ($-5 + 5 \log(1/\pi) - A_v$) give an absolute magnitude of $5.81_{+0.1}^{-0.1}$. Ritter and Kolb (1998) list visual magnitudes of 13.6 and 14.1. When using a trigonometric parallax to estimate the absolute magnitude of a star, a correction should be made for the Lutz-Kelker (LK) bias (Lutz & Kelker, 1973). Because of the galactic latitude and distance of TV Col, and the scale height of the stellar population of which it is a member, we do not use a uniform space density for calculating the LK bias, but use a density law that falls off as the -0.5 power of the distance at the distance of TV Col. This translates into $n = -3.5$ as the power in the parallax distribution. This n is then used in an LK algorithm modified by Hanson (H)(1979) to include the power law of the parent population. A correction of -0.03 ± 0.01 mag is derived for the LKH bias, which makes the absolute magnitude $5.89_{+0.12}^{-0.12}$ ($5.78_{+0.12}^{-0.12}$ with the A_v correction).

TV Col (Galactic coordinates: $l = 236.79$, $b = -30.60$) is well below the plane of the disk of the galaxy. From our absolute parallax and relative proper motion we derive a space velocity of 103 km s^{-1} (relative to our reference frame). The small difference between the relative proper motion derived for CD-32 2376 ($50.097 \text{ mas y}^{-1}$) and the absolute motions listed in the USNO ACT ($50.604 \text{ mas y}^{-1}$) and Tycho-2 ($49.519 \text{ mas y}^{-1}$) catalogs, see Table 6, suggests a small difference between relative and absolute proper motion. The velocity component perpendicular to the galactic plane, \mathbf{W} , is -5.1 km s^{-1} . Our new parallax places the star 187 parsecs below the sun, which locates it 195 parsecs below the galactic plane. Discussion of space velocity in cataclysmic variables can be reviewed in these papers: Sproats et al., 1996, Stehle et al., 1997, and van Paradijs et al., 1996.

4. The Mass of TV Col - an Unresolved Issue

ROSAT observations of TV Col (Vrtilek et al., 1996) indicated a ratio of X-ray luminosity to UV and optical luminosity of 0.2 in quiescence. Cropper et al.(1999) analyzed the continuum spectra obtained by Ginga to estimate a white dwarf mass of $1.2 \mathcal{M}_{\odot}$, while Ishida & Ezuka (1999) used *ASCA* data to derive a mass of $0.51^{+0.22}_{-0.41} \mathcal{M}_{\odot}$. Ramsay (2000) used *RXTE* data to determine a mass of $0.96^{+0.5}_{-0.2} \mathcal{M}_{\odot}$. Radial velocity measurements by Hellier (1993) provided a K_1 of $153 \pm 12 \text{ km s}^{-1}$ corresponding to a mass function of $0.085 \pm 0.020 \mathcal{M}_{\odot}$. The inclination is estimated to be $70^{\circ} \pm 3^{\circ}$ by the width and depth of the eclipse (Hellier et al., 1991). Assuming that it is a ZAMS star, Hellier (1993) estimated a secondary mass of $0.56 \mathcal{M}_{\odot}$ and a primary mass of $0.75 \pm 0.15 \mathcal{M}_{\odot}$ (using the Patterson (1984) equation). The secondary star is most likely a late K or early M (Beuermann, 2000, Smith & Dhillon, 1998), although it is reported as a K1 in SIMBAD, and a K1-5 in Ritter and Kolb (1998).

A measurement of the total separation of the components, combined with a parallax,

would provide a direct determination of their masses. The total estimated mass and measured period implies $a = 0.0080\text{AU}$. Our parallax would set the total separation at 21 microarcsecond (μarcsec) with individual orbits of 9 and 12 μarcsec . TV Col is a potential target for the Space Interferometry Mission (<http://sim.jpl.nasa.gov>). The component orbits are larger than the anticipated (1-2 μarcsec) SIM narrow angle astrometric measurement limits. With $\Delta V \sim 4$, much of the system flux is contributed by the WD. Longward of 700 nm the M dwarf - WD magnitude difference should decrease somewhat. The SIM sensitivity ($V_{lim} \sim 20$), wide bandpass (400-1000nm), and spectral resolution ($R=80$) should allow measurement of positions, magnitudes, and colors for both components. To derive a precise separation will require 5-10 such measurements to establish the component A and B orbits and the mass fraction. SIM could also provide an absolute parallax two orders of magnitude more precise than that reported here. Together orbits and parallax could provide masses with $\sim 5\%$ error.

5. Trigonometric Parallax and Absolute Magnitude of CD-32 2376

One of the reference stars in our field was a 10.46 magnitude Tycho Catalog Proper motion star. The HST parallax of CD-32 2376 was 7.83 ± 0.08 mas, which puts the distance at 127.7_{+1}^{-1} . We derived a relative $\mu_\alpha = 36.9 \pm 0.1$ mas y^{-1} and relative $\mu_\delta = 33.9 \pm 0.2$ mas y^{-1} for this star. Table 6 compares the HST proper motions with those listed in the Tycho 2 catalog (Høg et al., 2000) and the ACT (Urban et al., 1998). We attribute the difference in proper motion position angle to our very sparse and local reference frame.

6. Summary

HST trigonometric parallaxes can provide accurate distances to CVs. Accurate distances allow basic quantities such as absolute magnitude and mass transfer rate to be derived. Understanding the physics of CVs depends upon these derivations.

This research has made use of NASA’s Astrophysics Data System Abstract Service and the SIMBAD Stellar Database inquiry and retrieval system. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work is based on observation made with the NASA/ESA Hubble Space Telescope, which is operated by the Space Telescope Science Institute, of the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. The HST Astrometry Science Team receives support through NASA grant NAG5-1603. We thank Bill Welsh and Rob Robinson for helpful discussions and draft paper reviews. Denise Taylor and Laretta Nagel provided assistance at the Space Telescope Science Institute.

Table 1. Reference Star Spectral Types

Star	NMSU	WIYN	Adopted Spectral Type
Ref-1	G2 V	G2 IV	G2 V
Ref-2	G5 V	G1 V	G2 V
Ref-3	K1/2 V	K2 V	K2 V
Ref-4	K2 V	G9 V	G9 V

NMSU = New Mexico State University

WIYN = University of Wisconsin-Madison, Indiana University, Yale University, and the National Optical Astronomy Observatories

Table 2. Reference Star Photometry

Star	V^a	$B - V^a$	$V - K^b$	$J - K^b$	$M - D^c$	$M - T_2^c$
Ref-1	10.46	0.62 ± 0.02	1.50 ± 0.03	0.41 ± 0.04	0.01 ± 0.04	0.87 ± 0.02
Ref-2	14.66	0.59 ± 0.04	1.58 ± 0.04	0.34 ± 0.04	0.00 ± 0.04	0.92 ± 0.02
Ref-3	13.65	0.96 ± 0.03	2.20 ± 0.04	0.53 ± 0.04	-0.16 ± 0.04	1.18 ± 0.02
Ref-4	13.82	0.72 ± 0.03	1.70 ± 0.04	0.44 ± 0.04	-0.01 ± 0.04	1.14 ± 0.02

^aB, V, and I are from New Mexico State

^bJ, K are from 2MASS

^cM, D, T_2 are Washington-DDO filters

Table 3. Reference Star Spectroscopic Parallaxes

Star	V	M_V^a	A_v^b	m-M- A_v	π_{abs}
Ref-1	10.46	4.7 ± 0.1	0.1	5.7	0.0076 ± 0.0007
Ref-2	14.66	4.7 ± 0.1	0.1	9.9	0.0017 ± 0.0004
Ref-3	13.65	6.2 ± 0.5	0.1	7.4	0.0022 ± 0.0002
Ref-4	13.82	5.7 ± 0.3	0.1	8.0	0.0025 ± 0.0002

^a M_V from AQ2000

^b A_V from Schlegel *et al.* 1998

Table 4. TV Col and Reference Star Data

Star	ξ^a	η^a	σ_ξ (mas)	σ_η (mas)	π_{abs} (mas)
TV Col	31.354	667.018	0.34	0.45	2.717
Ref-1 (CD32-2376)	101.968	730.702	0.30	0.37	7.831
Ref-2	2.500	784.643	0.44	0.72	1.681
Ref-3	35.568	659.404	0.34	0.54	2.193
Ref-4	-364.898	695.884	0.4	0.5	2.502

^a ξ and η are relative positions in arcseconds

Table 5. TV Col Parallax and Proper Motion

Parameter	Value
<i>HST</i> study duration	2.5 y
Number of observation sets	10
Number of ref. stars	4
<i>HST</i> Parallax	2.7 ± 0.11 mas
<i>HST</i> Distance	368_{+17}^{-15} parsecs
<i>HST</i> Relative Proper Motion μ_α	25.99 ± 0.1 mas y^{-1}
<i>HST</i> Relative Proper Motion μ_δ	9.67 ± 0.2 mas y^{-1}
<i>HST</i> Relative Proper Motion (μ) in p.a.	27.72 ± 0.22 mas y^{-1} 69.6°

^athe relative proper motion position angle is likely to vary significantly from absolute because of the sparse reference frame (indicated by p.a. of CD-32 2376)

Table 6. CD-32 2376 Parallax and Proper Motion

Parameter	Value
<i>HST</i> Parallax	7.83 ± 0.08 mas
<i>HST</i> Distance	127.7_{+1}^{-1} parsecs
<i>HST</i> Relative Proper Motion μ_α	36.9 ± 0.1 mas y^{-1}
<i>HST</i> Relative Proper Motion μ_δ	33.9 ± 0.1 mas y^{-1}
<i>HST</i> Relative Proper Motion (μ)	50.097 ± 0.14 mas y^{-1}
in p.a.	47.4°
<i>Tycho-2</i> μ	49.519 ± 1.6 mas y^{-1}
in p.a.	37°
USNO ACT μ	50.604 ± 4.3 mas y^{-1}
in p.a.	35°

Table 7. Distance Estimates to TV Col

Reference	Distance in parsecs	Method
Patterson(1984)	160	Disk properties
Patterson(1994)	400	Photometric parallax of the secondary
Mouchet et al.(1981)	< 500	Weak UV interstellar absorption
Bonnet-Bidaud et al.(1985)	500	Infrared photometry of secondary
Buckley & Tuohy (1989)	> 500	Xray distance
<i>HST</i> (2000)	368_{+17}^{-15}	Trigonometric parallax, this paper

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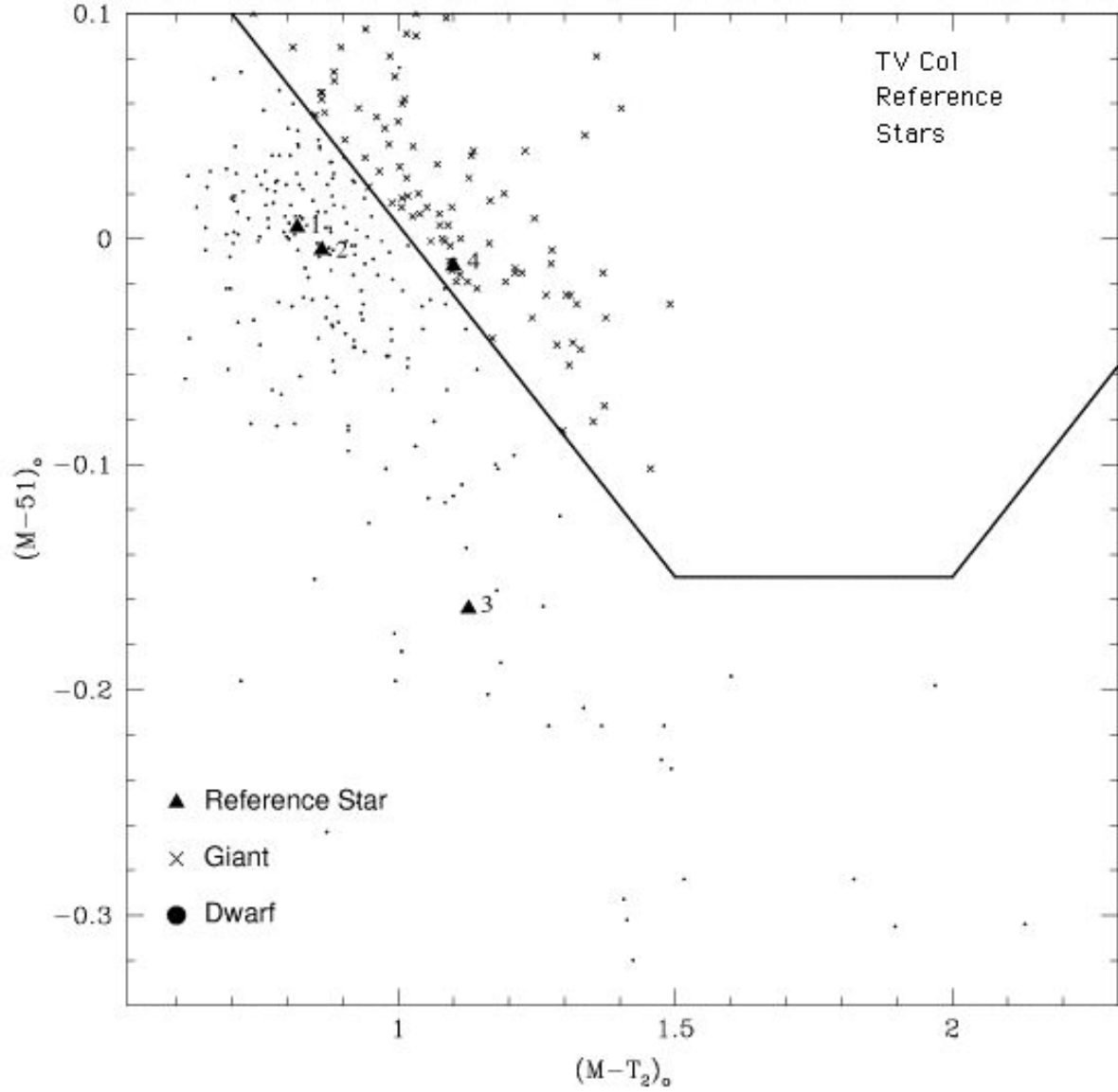


Fig. 1.— Astrometric reference stars plotted on the M-D vs M-T₂ plane. The values have been corrected for absorption. Also plotted are known dwarf (·) and giant (×) stars. Ref-4 is ambiguous. A dwarf luminosity classification for all reference stars results in a lower χ^2 for our TV Col parallax solution.

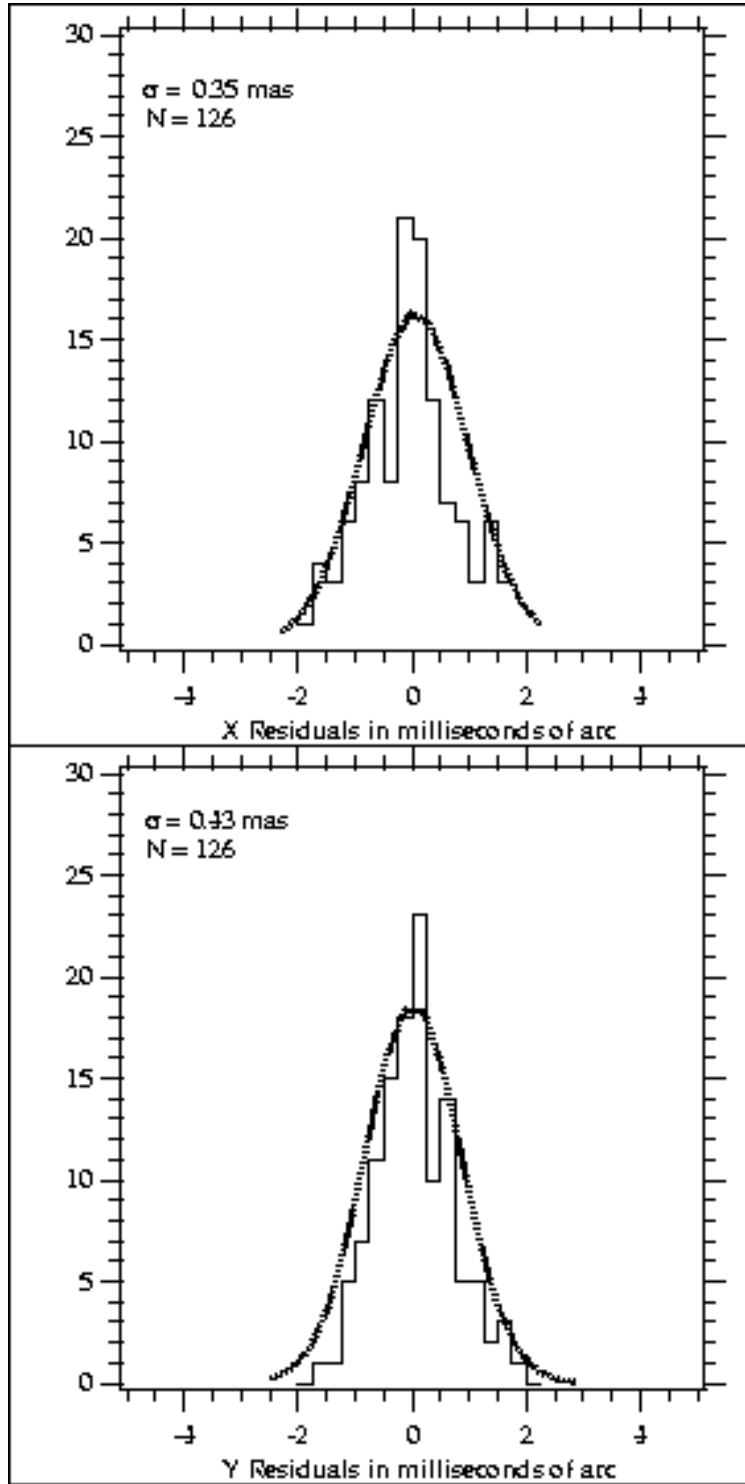


Fig. 2.— Histograms of x and y residuals obtained from modelling TV Col and its reference frame. Distributions are fit with Gaussians.