Cepheids in Clusters, Reddening, and the PZPO

(Budapest extended)

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Overview Talk

- IAU 376 Budapest, 17-21 April 2023
  "At the cross-roads of astrophysics and cosmology: Period–luminosity relations in the 2020s"

  "Primary PL-Relation Calibrators in the Milky Way: Cepheids and RR Lyrae

  Physical basis, Calibration, and Applications"

- PL-relation: Calibration
  - Distance scale
    - Cepheids in Clusters
    - Reddening

Calibration

$M - m_0 = 5 \log(d/10$ [pc])

$M = F$(P, [Fe/H])

$\omega = 10^{0.2(m_0 - F - 5)}$

- $\omega_{\rm G}$ - PZPO
  DR2: -29 μas (QSOs),
  -46 ± 13 (Riess+ 2018), -49 ± 18 (Gr18) (CEP)
  -56 (Murareva+ 2018), -42 (Layden+ 2019) (RRL)

  DR3: -17 μas (QSOs)
  Lindegren et al. (2021; L21)
  Maíz Apellániz (2022, A&A 657; MA22)
  Groenewegen (2021, A&A 654; G21)
- $\omega_{\rm G}$ - PZPO + $\Delta\pi$

Hipparcos ⇒ HST ⇒ GDR3

Benedict et al. (2007 AJ 133; 2022 AJ 163)
Riess et al. (2014, ApJ 785; 2018, ApJ 855)

Name	$\pi \pm \sigma_\pi$ (rev. Hipparcos)	$\pi \pm \sigma_\pi$ (HST)	$\pi \pm \sigma_\pi$ (GDR3)	GoF
η Aql	2.36 ± 1.04	3.71 ± 0.07	3.67 ± 0.19	29
β Dor	3.24 ± 0.36	3.14 ± 0.16	2.93 ± 0.14	47
δ Cep	3.77 ± 0.17	3.66 ± 0.15	3.56 ± 0.15	31
FF Aql	2.11 ± 0.33	2.81 ± 0.18	1.91 ± 0.07	1.5
l Car	2.09 ± 0.29	2.01 ± 0.20	1.98 ± 0.11	24
RT Aur	-1.10 ± 1.41	2.40 ± 0.19	1.81 ± 0.12	66
T Vul	2.71 ± 0.43	1.90 ± 0.23	1.69 ± 0.06	5.3
Y Sgr	2.64 ± 0.45	2.13 ± 0.29	1.97 ± 0.06	13
X Sgr	3.31 ± 0.26	3.00 ± 0.18	2.81 ± 0.14	5.1
ζ Gem	2.37 ± 0.30	2.78 ± 0.18	3.07 ± 0.22	22
W Sgr	3.75 ± 1.12	2.28 ± 0.20	2.37 ± 0.18	36
SY Aur	-1.84 ± 1.72	0.428 ± 0.054	0.427 ± 0.020	2.5
SS CMa	0.40 ± 1.78	0.389 ± 0.029	0.287 ± 0.013	4.0
XY Car	-1.02 ± 0.88	0.438 ± 0.048	0.378 ± 0.014	2.1
VX Per	0.87 ± 1.52	0.420 ± 0.076	0.364 ± 0.017	3.5
VY Car	0.36 ± 1.42	0.586 ± 0.045	0.554 ± 0.017	-2.4
WZ Sgr	3.50 ± 1.22	0.512 ± 0.039	0.574 ± 0.028	-1.1
S Vul		0.322 ± 0.040	0.205 ± 0.020	1.1
X Pup	1.97 ± 1.26	0.277 ± 0.048	0.376 ± 0.020	1.2

Hipparcos $\Rightarrow$ HST $\Rightarrow$ GDR3

Benedict et al. (2011 AJ 142)

Name	Type	$\pi \pm \sigma_\pi$ (rev. Hipparcos)	$\pi \pm \sigma_\pi$ (HST)	$\pi \pm \sigma_\pi$ (GDR3)	GoF
SU Dra	RRab	0.20 ± 1.13	1.42 ± 0.16	1.332 ± 0.014	0.4
RR Lyr	RRab	3.46 ± 0.64	3.77 ± 0.13	3.985 ± 0.027	0.9
UV Oct	RRab	2.44 ± 0.81	1.71 ± 0.10	1.838 ± 0.012	0.0
XZ Cyg	RRab	2.29 ± 0.84	1.67 ± 0.17	1.586 ± 0.015	4.1
RZ Cep	RRc	0.59 ± 1.48	2.54 ± 0.19	2.401 ± 0.012	-0.3
VY Pyx	BL Her	5.01 ± 0.44	6.44 ± 0.23	3.950 ± 0.019	-3.6
κ Pav	W Vir	6.52 ± 0.77	5.57 ± 0.28	5.245 ± 0.122	38

Proxys

- Cepheids with Companions
  Polaris A: Hipparcos revised parallax 7.54 ± 0.11 mas
  Polaris B: GDR3 7.287 ± 0.018

  Kervella et al. (2019) "proper motion anomaly"

- Cepheids in Clusters

Breuval et al. 2020, A&A 643
22 spatially resolved companions +
14 Cepheids that are candidate cluster members
DR2 + offset

α	β	σ	Band	
-2.481 ± 0.244	-3.731 ± 0.050	0.18	V	-46 mas
-3.257 ± 0.163	-5.323 ± 0.026	0.14	K	-46 mas
-3.332 ± 0.177	-5.965 ± 0.029	0.17	WH(T)	-46 mas
-3.340 ± 0.180	-6.010 ± 0.030	0.16	WH(T)	-31 mas
-3.322 ± 0.175	-5.904 ± 0.029	0.18	WH(T)	-61 mas

Cepheids in Open Clusters

- Zhou & Chen 2021, MNRAS 504
  33 Cepheids in OCs (DR2/3)
  Medina et al. 2021, MNRAS 505
  19 Cepheids in OCs (DR2)
- Riess et al. (2022, ApJ 938)
  17 Cepheids, HST photometry
  DR2 membership (Cantat-Gaudin et al. 2020)
- Hao et al. (2022, A&A 668)
  39 "probable" Cepheids in OCs, DR3
  Lin et al. (2022, ApJ 938), DR2 + DR3.
- Cruz Reyes & Anderson (2023, A&A 672)
  34 Cepheids in 28 OCs, DR3
- Groenewegen (this work)

Cluster Cepheids

Cluster	$\pi \pm \sigma_\pi$ (Riess+)	$\pi \pm \sigma_\pi$ (Cruz Reys+)	$\pi \pm \sigma_\pi$ (Hao+)	$\pi \pm \sigma_\pi$ (Gr23)	N	R ($'$)
Berkeley 58	336 ± 8	336 ± 7	290 ± 20	302 ± 11	85	4.0
NGC 129	559 ± 7	557 ± 7	530 ± 30	529 ± 10	290	6.5
FSR 0951	594 ± 7	610 ± 7	570 ± 30	566 ± 11	128	6.8
vdBergh 1	579 ± 10	585 ± 10	550 ± 40	543 ± 13	50	1.9
Ruprecht 79	274 ± 8	281 ± 7	240 ± 20	244 ± 11	99	2.8
NGC 5662	1322 ± 7	1336 ± 6	1300 ± 30	1292 ± 12	225	18.1
Lynga 6	408 ± 9	421 ± 8	380 ± 40	383 ± 11	157	5.2
NGC 6067	496 ± 7	513 ± 7	470 ± 30	473 ± 11	671	4.5
NGC 6087	1057 ± 7	1073 ± 7	1020 ± 30	1025 ± 11	154	7.7
IC 4725	1540 ± 7	1554 ± 6	1520 ± 50	1514 ± 12	325	11.6
NGC 6649	508 ± 8	514 ± 7	470 ± 50	474 ± 11	301	3.1
UBC 129	886 ± 7	880 ± 7	850 ± 20	852 ± 11	116	11.7
UBC 130	428 ± 8	425 ± 9	400 ± 20	396 ± 11	36	2.4
NGC 7790	331 ± 8	322 ± 7	290 ± 30	293 ± 11	114	3.0
{ UBC 231	356 ± 8	345 ± 8		312 ± 11	56	7.9
OC – 0717			370 ± 10	370 ± 10	64	24.4
{ NGC 3496	439 ± 8			408 ± 10	464	7.6
Ruprecht 93		482 ± 7		448 ± 11	169	4.7

Spatial covariance sets limit on accuracy!

Different PZPO

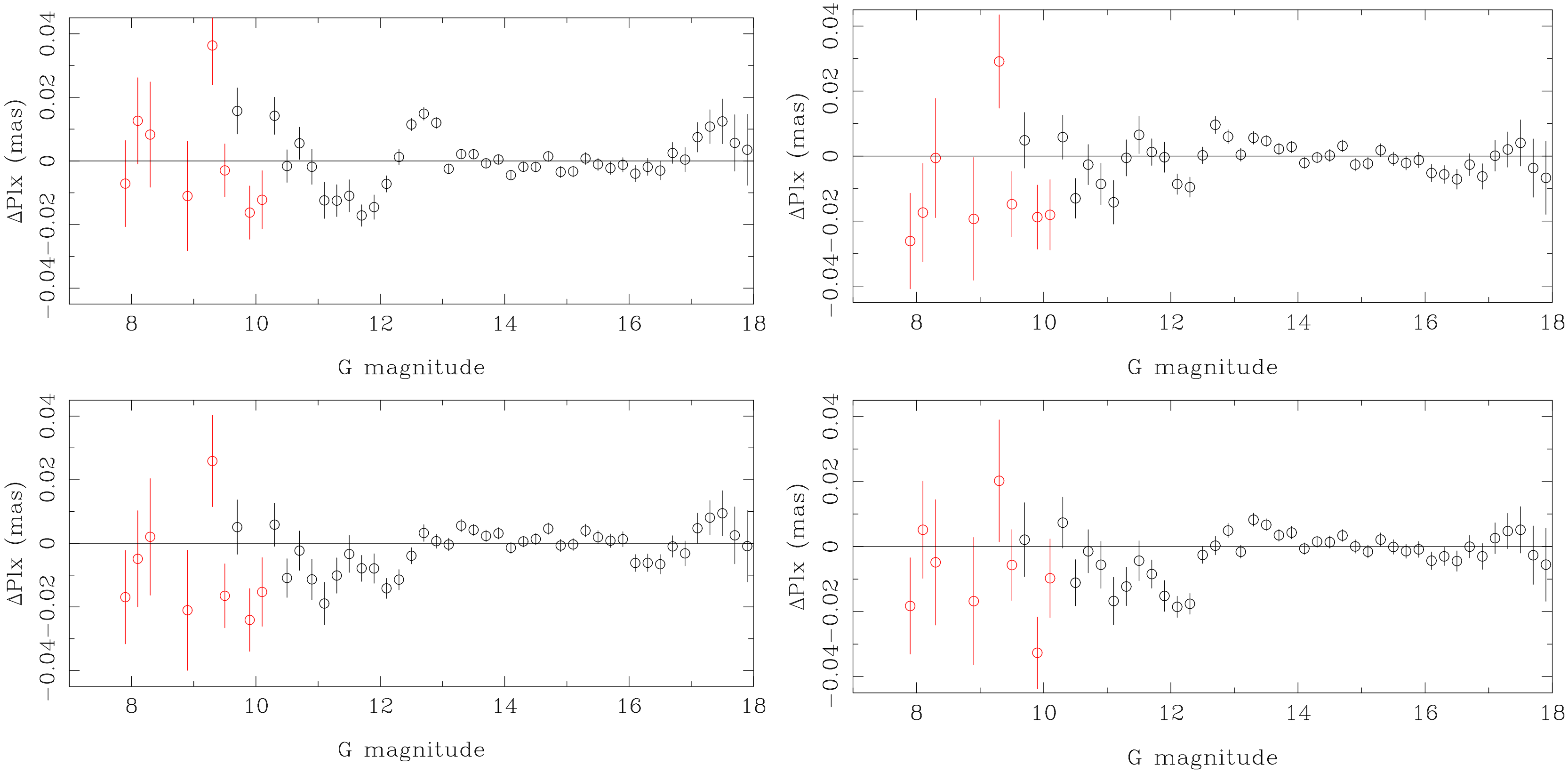
Cluster	$\pi \pm \sigma_\pi$ (Cruz Reys+) (L21)	$\pi \pm \sigma_\pi$ (Gr23) (L21)	$\pi \pm \sigma_\pi$ (Gr23) (MA22)	$\pi \pm \sigma_\pi$ (Gr23) (G21)	$\pi \pm \sigma_\pi$ (Gr23) (none)
Berkeley 58	336 ± 7	330 ± 11	329 ± 11	338 ± 11	302 ± 11
NGC 129	557 ± 7	558 ± 10	556 ± 10	564 ± 10	529 ± 10
FSR 0951	610 ± 7	607 ± 11	607 ± 11	588 ± 11	566 ± 11
vdBergh 1	585 ± 10	585 ± 12	582 ± 12	576 ± 13	543 ± 13
Ruprecht 79	281 ± 7	275 ± 11	274 ± 11	256 ± 11	244 ± 11
NGC 5662	1336 ± 6	1328 ± 12	1329 ± 12	1358 ± 12	1292 ± 12
Lynga 6	421 ± 8	420 ± 11	417 ± 11	400 ± 11	383 ± 11
NGC 6067	513 ± 7	514 ± 11	513 ± 11	495 ± 11	473 ± 11
NGC 6087	1073 ± 7	1065 ± 11	1066 ± 11	1065 ± 11	1025 ± 11
IC 4725	1554 ± 6	1552 ± 12	1551 ± 12	1544 ± 12	1514 ± 12
NGC 6649	514 ± 7	514 ± 11	511 ± 11	487 ± 11	474 ± 11
UBC 129	880 ± 7	882 ± 11	880 ± 11	886 ± 11	852 ± 11
UBC 130	425 ± 9	426 ± 11	423 ± 12	431 ± 12	396 ± 11
NGC 7790	322 ± 7	321 ± 11	320 ± 11	341 ± 11	293 ± 11
UBC 231	345 ± 8	350 ± 12	349 ± 12	371 ± 12	312 ± 11
Ruprecht 93	482 ± 7	484 ± 11	484 ± 11	473 ± 11	448 ± 11

Different PZPO

Cruz Reyes & Anderson (CrA) - Riess = 5.7 ± 2.0 μas for 15 clusters
This Work - Hao = 0.8 $\pm$ 2.5 μas for 20 clusters
This Work - CrA = -35.2 ± 2.0 μas over 30 clusters (effect PZPO)

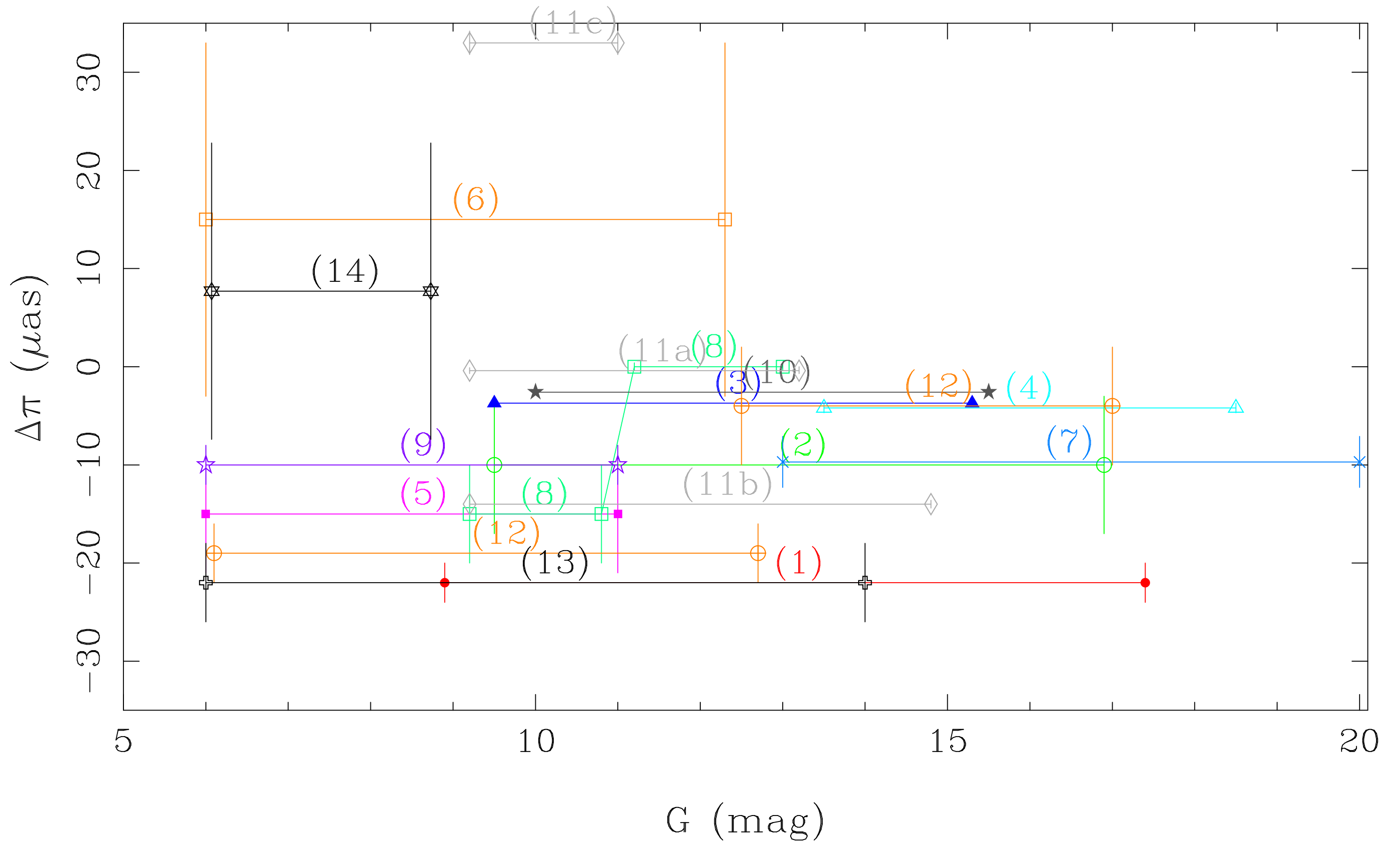
This Work - CrA (L21) = -0.3 ± 2.0 μas over 30 clusters
This Work (MA22-L21) = -1.3 ± 2.0 μas
This Work (G21-L21) = $+1.9 \pm 2.0$ μas

Offsets



Residuals between individual and cluster parallaxes summed over all clusters and plotted against G mag. No correction (top left), L21 (top right), MA22 (lower left), G21 (lower right).

Counter correction



(1) Bhardwaj+21 RRL; (2) Gilligan+21 RRL; (3) Huang+21 RC; (4) Ren+21 WUMa EBs; (5) Riess+21 DCEP LMC; (6) Stassun&Torres 2021 EBs; (7) V&B21 GCs; (8) Zinn21 asteroseismology; (9) Flynn+22 OCs/GCs; (10) Wang+22 giants; (11) Khan+23 RGs asteroseismology, *Kepler* (a), K2 (b), TESS-SCVZ (c); (12) Cruz R.&Anderson23 OCs & MW DCEPs; (13) Molinaro+23 MW DCEPS; (14) Gr23 dynamical parallax.

Reddening

$$W = a - R \cdot (b - c) = W_0$$
$$R = A_{\rm a}/(A_{\rm b} - A_{\rm c})$$

Fitzpatrick (1999)
Cardelli, Clayton, & Mathis (1989) + O'Donnell 1994 (hereafter COD)
Wang & Chen (2019 ApJ 877; arXiv230109146)

$$\lambda_{\rm eff} = \frac{\int \lambda \cdot R(\lambda) M(\lambda) 10^{-0.4 \cdot A_\lambda}\ d\lambda}{\int R(\lambda) M(\lambda) 10^{-0.4 \cdot A_\lambda}\ d\lambda}$$

Standard is $\log g = 2.0$ and $M = 5$ M$_\odot$ MARCS models

effective wavelengths

Filter	Model 1	2	3	4	5	6	7
G	702	769	658	701	700	669	736
Bp	563	578	538	561	559	549	577
Rp	794	826	785	795	796	781	811
$V_{\rm J}$	556	560	551	556	555	553	560
$I_{\rm c}$	790	795	788	790	790	787	793
$V_{\rm ogleIV}$	541	543	537	541	540	538	544
$I_{\rm ogleIV}$	798	803	796	799	799	795	802
J	1237	1240	1231	1236	1236	1234	1238
H	1643	1648	1641	1643	1643	1641	1645
K	2153	2154	2153	2163	2153	2152	2154
F555W	545	548	540	544	544	541	549
F814W	814	828	810	814	814	807	823
F160W	1532	1541	1527	1532	1532	1531	1534

Model 1: $T_{\rm eff} = 5000$ K, [Z]= $+0.0$, $E(B-V)$= 0.5,

Model 2: $T_{\rm eff} = 3600$ K, [Z]= $+0.0$, $E(B-V)$= 0.5,

Model 3: $T_{\rm eff} = 7000$ K, [Z]= $+0.0$, $E(B-V)$= 0.5,

Model 4: $T_{\rm eff} = 5000$ K, [Z]= -0.5, $E(B-V)$= 0.5,

Model 5: $T_{\rm eff} = 5000$ K, [Z]= -1.0, $E(B-V)$= 0.5,

Model 6: $T_{\rm eff} = 5000$ K, [Z]= $+0.0$, $E(B-V)$= 0.1,

Model 7: $T_{\rm eff} = 5000$ K, [Z]= $+0.0$, $E(B-V)$= 1.0.

Relative reddenings

Filter	$\lambda_{\rm eff}$ (Model 1/2/3)	$A_\lambda/A_{\rm V}$ F99	$A_\lambda/A_{\rm V}$ COD	$A_\lambda/A_{\rm V}$ W23
		$R_{\rm V} = 3.3$	$R_{\rm V} = 3.1$	$R_{\rm V} = 3.4$
G	7020/7690/6580	0.697/0.601/0.769	0.751/0.655/0.810	0.703/0.610/0.776
Bp	5630/5780/5380	0.950/0.919/1.008	0.969/0.937/1.029	0.968/0.935/1.027
Rp	7940/8260/7850	0.570/0.532/0.581	0.617/0.569/0.631	0.579/0.543/0.590
$V_{\rm o}$	5410/5430/5370	1.001/0.996/1.011	1.021/1.016/1.032	1.020/1.015/1.030
$I_{\rm o}$	7980/8030/7960	0.565/0.559/0.567	0.611/0.603/0.614	0.575/0.569/0.577
J	12370/12400/12310	0.261/0.260/0.263	0.287/0.286/0.289	0.249/0.247/0.252
H	16430/16480/16410	0.165/0.164/0.166	0.182/0.181/0.182	0.138/0.138/0.139
$K_{\rm s}$	21530/21540/21530	0.112/0.112/0.112	0.118/0.117/0.118	0.079/0.079/0.079
F555W	5450/5480/5400	1.011/0.984/1.003	1.011/1.004/1.024	1.011/1.003/1.022
F814W	8140/8280/8100	0.587/0.530/0.551	0.587/0.566/0.593	0.557/0.541/0.561
F160W	15320/15410/15270	0.203/0.182/0.185	0.203/0.201/0.204	0.160/0.158/0.161
			R	
WG		1.831/1.557/1.798	2.136/1.781/2.034	1.807/1.558/1.775
WVI		1.296/1.279/1.279	1.490/1.463/1.471	1.291/1.275/1.276
WJK		0.751/0.756/0.740	0.694/0.698/0.685	0.465/0.468/0.459
WH		0.414/0.402/0.409	0.479/0.461/0.474	0.352/0.342/0.349

Example: CR Car

Filter	Observed	Dereddened magnitudes		
		F99/ Model 1	COD/ Model 1	W23/ Model 3
		$R_V = 3.3$	$R_V = 3.1$	$R_V = 3.4$
		$E(B-V) = 0.5$	$E(B-V) = 0.5$	$E(B-V) = 0.1$
G	11.063	9.909	9.875	10.655
Bp	11.880	10.311	10.347	11.341
Rp	10.137	9.199	9.161	9.827
V	11.511	9.859	9.928	10.986
I	10.007	9.074	9.040	9.704
J	8.846	8.415	8.392	8.714
H	8.188	7.916	7.900	8.115
K	8.058	7.873	7.871	8.017
F555W	11.750	10.080	10.150	11.213
F814W	9.973	9.003	9.044	9.678
F160W	8.384	8.049	8.063	8.299
WG	7.751	7.795	7.621	7.780
WVI	7.921	7.984	7.808	7.926
WJK	7.479	7.475	7.489	7.504
WH	7.698	7.633	7.636	7.707

WG= $G - 1.90 \cdot (Bp - Rp)$

WVI= $I - 1.387 \cdot (V - I)$

WJK= $K - 0.735 \cdot (J - K)$

WH= $F160W - 0.386 \cdot (F555W - F814W)$

THE END