

## THE SOLAR NEIGHBORHOOD. XXVI. AP Col: THE CLOSEST (8.4 pc) PRE-MAIN-SEQUENCE STAR

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### ABSTRACT

We present the results of a multi-technique investigation of the M4.5Ve flare star AP Col, which we discover to be the nearest pre-main-sequence star. These include astrometric data from the CTIO 0.9 m, from which we derive a proper motion of  $342.0 \pm 0.5$  mas yr<sup>-1</sup>, a trigonometric parallax of  $119.21 \pm 0.98$  mas ( $8.39 \pm 0.07$  pc), and photometry and photometric variability at optical wavelengths. We also provide spectroscopic data, including radial velocity ( $22.4 \pm 0.3$  km s<sup>-1</sup>), lithium equivalent width (EW) ( $0.28 \pm 0.02$  Å), H $\alpha$  EW ( $-6.0$  to  $-35$  Å),  $v \sin i$  ( $11 \pm 1$  km s<sup>-1</sup>), and gravity indicators from the Siding Spring 2.3 m WiFeS, Lick 3 m Hamilton echelle, and Keck-I HIRES echelle spectrographs. The combined observations demonstrate that AP Col is the closer of only two known systems within 10 pc of the Sun younger than 100 Myr. Given its space motion and apparent age of 12–50 Myr, AP Col is likely a member of the recently proposed  $\sim 40$  Myr old Argus/IC 2391 Association.

*Key words:* astrometry – parallaxes – solar neighborhood – stars: low-mass – stars: pre-main sequence – techniques: spectroscopic

*Online-only material:* color figures

## 1. INTRODUCTION

For decades, young stars ( $\lesssim 600$  Myr) were thought to reside only in giant star-forming regions such as the Orion Nebula, the Taurus-Auriga dark cloud, the Scorpius-Centaurus star-forming region, or other distant large molecular clouds. Indeed, the only relatively young stars near the Sun seemed to be in the Pleiades (Trumpler 1921; age  $\sim 125$  Myr, Stauffer et al. 1998), the Sirius-Ursa Major moving group (Eggen 1958; age  $\sim 300$  Myr, Famaey et al. 2008), and the Hyades (Eggen 1958; age  $\sim 600$  Myr, Famaey et al. 2008). In the 1980s, this picture changed as the stars TW Hydra and  $\beta$  Pictoris were identified as isolated T Tauri stars. Eventually, both TW Hydra (de la Reza et al. 1989) and  $\beta$  Pictoris (Barrado y Navascués et al. 1999) were found to be members of sparse kinematic associations of pre-main-sequence stars under 100 Myr old, and a number of other nearby associations (Zuckerman & Song 2004; Torres et al. 2008) were identified.

Currently, there are several reported associations less than 100 Myr old with members closer than 100 pc, comprising associations such as  $\sim 8$  Myr old TW Hydra (now with over 30 members),  $\sim 12$  Myr  $\beta$  Pictoris,  $\sim 70$  Myr AB Doradus, and  $\sim 40$  Myr Argus/IC 2391. These clusters, while sparse and not gravitationally bound, are nearby easy-to-examine windows into the history and processes of star formation, far younger and far more accessible than classical open clusters such as the Pleiades (133 pc, Soderblom et al. 2005).

The X-ray active M dwarf AP Col (= LP 949-015, LTT 2449, SIPS J0604-3433, 2MASS J06045215-3433360) was identified as a UV-Ceti-type flare star as early as 1995 (Ball & Bromage 1995), whereupon it was given its variable star designation. It was studied by Scholz et al. (2005) as one of three active M

dwarfs detected within a predicted distance of 8 pc, and again by Riaz et al. (2006), where the star’s potential youth and proximity was again noted. It was also targeted for Lucky Imaging by Bergfors et al. (2010), and for Speckle Imaging with the USNO Specklecam on the CTIO 4 m by B. Mason & W. Hartkopf (2011, private communication). The Research Consortium on Nearby Stars (RECONS<sup>6</sup>), which searches for nearby stars in the southern sky (Henry et al. 2006), also identified this star as potentially nearby, and it was put on the target list of the Cerro Tololo Inter-American Parallax Investigation (CTIOPI) in 2004. As described in this work, the star was more recently investigated at the Lick, Keck, and Siding Spring Observatories.

In conjunction with the new data presented here, we will first show that the observed characteristics of AP Col are signs of a youthful age of less than 100 Myr and not interactions with a close companion. We will then argue that its age and kinematics match those of the Argus association defined by Torres et al. (2008).

## 2. OBSERVATIONS

### 2.1. Astrometry and Photometry

All new astrometric and photometric observations were carried out at the CTIO 0.9 m telescope, initially (1999–2003) under the aegis of the National Optical Astronomy Observatory (NOAO) Surveys Program, and later (2003–present) via the Small and Moderate Aperture Research Telescope System (SMARTS) Consortium, as part of the long running CTIOPI program (Jao et al. 2005).

The 158  $V_J$  filter observations of AP Col used in our astrometric and relative photometry sequences were obtained on 27 nights between 2004 September and 2011 March, utilizing the central  $1024 \times 1024$  pixels of the 0.9 m telescope’s  $2048 \times$

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<sup>6</sup> <http://www.recons.org/>

**Table 1**  
AP Col Spectroscopic Observations Summary

UT Date	Instrument	Setup	Coverage (Å)	Resolving <sup>a</sup> Power	S/N	$\lambda$ of S/N <sup>b</sup> (Å)	H $\alpha$ EW (Å)	Li $\lambda$ 6708 EW (Å)	RV <sup>c</sup> (km s <sup>-1</sup> )	$v \sin i$ (km s <sup>-1</sup> )
2011 Jan 8	WiFeS	$R_{7000}$ /RT480 <sup>d</sup>	5500–7000	7,000	30	6300	$-7.5 \pm 1.0$	$0.25 \pm 0.1$	$21.3 \pm 1.0$	
2011 Jan 8	WiFeS	$R_{7000}$ /RT480	5500–7000	7,000	25	6300	$-8.0 \pm 1.0$	$0.25 \pm 0.1$	$24.1 \pm 0.8$	
2011 Jan 25	Hamilton	800 $\mu$ m slit, Dewar 6	3850–8850	40,000	25	6700	$-35 \pm 3$	$0.19 \pm 0.03$	$23 \pm 1$	
2011 Jan 25	WiFeS	$B/R_{3000}$ /RT560	3400–9650	3,000	60	7400	$-28 \pm 3$			
2011 Jan 25	WiFeS	$B/R_{3000}$ /RT560	3400–9650	3,000	60	7400	$-26 \pm 3$			
2011 Jan 25	WiFeS	$B/R_{3000}$ /RT560	3400–9650	3,000	60	7400	$-35 \pm 3$			
2011 Jan 26	WiFeS	$B/R_{3000}$ /RT560	3400–9650	3,000	60	7400	$-12 \pm 3$			
2011 Feb 11	WiFeS	$R_{7000}$ /RT480	5500–7000	7,000	30	6300	$-13.5 \pm 1.0$	$0.25 \pm 0.05$	$21.5 \pm 0.9$	
2011 Feb 24	WiFeS	$R_{7000}$ /RT480	5500–7000	7,000	25	6300	$-7.5 \pm 1.0$	$0.3 \pm 0.05$	$20.0 \pm 0.8$	
2011 Mar 16	WiFeS	$R_{7000}$ /RT480	5500–7000	7,000	35	6300	$-12.1 \pm 1.0$	$0.25 \pm 0.1$	$24.1 \pm 1.0$	
2011 Mar 17	WiFeS	$R_{7000}$ /RT480	5500–7000	7,000	40	6300	$-6.5 \pm 1.0$	$0.25 \pm 0.05$	$23.2 \pm 1.0$	
2011 Mar 17	WiFeS	$R_{7000}$ /RT480	5500–7000	7,000	50	6300	$-6.0 \pm 1.0$	$0.3 \pm 0.05$	$22.5 \pm 1.1$	
2011 Mar 17	HIRES	Red Collimator	3580–7950	50,000	20	6700	$-7.3 \pm 0.5$	$0.37 \pm 0.03$	$22.3 \pm 0.3$	$11 \pm 1$

**Notes.**

<sup>a</sup> Resolution is measured from the FWHM of single arc lines in our comparison spectra.

<sup>b</sup> Wavelength where S/N measurement is made in the spectrum.

<sup>c</sup> RV errors for WiFeS are internal errors with reference to the standards.

<sup>d</sup> RT480 and RT560 are dichroics for the beam splitter.

2046 Tek CCD with a  $0''.401$  pixel scale and CTIO’s  $V_J$ ,  $R_{KC}$ , and  $I_{KC}$ <sup>7</sup> filters. Additional details of the observing protocols for the astrometry and photometry programs can be found in Jao et al. (2005) and Winters et al. (2011), respectively.

The same setup was used to obtain four nights of  $VRI$  photometry, interleaved with standard star observations from Graham (1982), Landolt (1992), and Landolt (2007) at various air masses. The photometric observations were reduced via a custom IRAF pipeline and transformed onto the Johnson–Kron–Cousins system, as described in Henry et al. (2006).

## 2.2. Spectroscopy

### 2.2.1. CTIO 1.5 m RCspec

To measure a spectral type, AP Col was observed on the CTIO 1.5 m on UT 2004 March 14 using the 32/I grating setup (6000–9600 Å,  $R = 1500$ ). The resulting spectrum was reduced using standard IRAF procedures and then classified as M4.5Ve using the ALLSTAR code (Henry et al. 2002), which compares it to spectral standards on the Kirkpatrick et al. (1991) system.

### 2.2.2. SSO 2.3 m WiFeS IFU

To measure a preliminary radial velocity, H $\alpha$ , and Li I  $\lambda$ 6708 line strengths, AP Col was observed several times during 2011 January–March with the Wide Field Spectrograph (WiFeS) on the Australian National University 2.3 m at Siding Spring Observatory. WiFeS (Dopita et al. 2007, 2010) is a new dual-beam image slicing integral field spectrograph that provides a nominal  $25'' \times 38''$  field of view with  $0''.5$  pixels to two gratings and camera assemblies simultaneously using a beam splitter, one “beam” optimized for red spectra, the other for blue. AP Col was observed in single-beam mode with the  $R7000$  grating, yielding a resolving power of  $R \simeq 7000$  and wavelength coverage of 5500–7000 Å. Following S. J. Murphy et al. (2011, in preparation), we used WiFeS in single-star mode with twice the spatial binning ( $1''$  spatial pixels) and optimally extracted

and combined the five image slices (effectively a  $5''$  diameter aperture around the object) that contain the majority of the stellar flux.

WiFeS has a measured radial velocity precision capability of  $\sim 2$  km s<sup>-1</sup> per epoch at this resolution and signal-to-noise ratio (Table 1; S. J. Murphy et al. 2011, in preparation). We therefore observed AP Col seven times on different nights to improve the mean velocity and check for changes in H $\alpha$  emission line strength. These observations motivated further high-resolution observations with the Lick Hamilton echelle and Keck HIRES echelle, discussed in the next sections.

In addition to the  $R7000$  observations, AP Col was observed on 2011 January 25–26 with the  $B3000$  and  $R3000$  gratings in dual-beam mode, yielding a resolving power of  $R \simeq 3000$  and wavelength coverage of 3400–9560 Å. The spectra from each beam were independently flux-calibrated and corrected for telluric features, and combined into a single spectrum. Details about all the WiFeS observations are presented in Table 1.

### 2.2.3. Lick Shane 3 m Hamilton Echelle

Contemporaneous with the low-resolution WiFeS spectra, additional measurements of radial velocity, H $\alpha$ , and Li I  $\lambda$ 6708 EW were obtained at the Lick Observatory Shane 3 m telescope with the Hamilton echelle spectrograph (Vogt 1987), which is located at the telescope’s Coudé focus. The spectra were bias-subtracted, flat-fielded, extracted, and wavelength-calibrated with ThAr arc lamp spectra. Further details on data reduction for the Hamilton echelle with IRAF tasks are outlined in detail in Lick Technical Report No. 74.<sup>8</sup>

Details about the observations are presented in Table 1. We note that AP Col, at declination  $-34$ , is at the southern limit of what can reasonably be observed from Lick Observatory; the average air mass during observations was 3.3.

### 2.2.4. Keck-I 10 m HIRES Echelle

More precise measurements of radial velocity and  $v \sin i$  were obtained on the Keck-I 10 m telescope on Mauna Kea using the HIRES echelle spectrograph (Vogt et al. 1994). All HIRES data

<sup>7</sup> The central wavelengths for  $V_J$ ,  $R_{KC}$ , and  $I_{KC}$  are 5475, 6425, and 8075 Å, respectively. The subscript “ $J$ ” indicates Johnson, “ $KC$ ” indicates Kron–Cousins (usually known as “Cousins”), and are hereafter omitted.

<sup>8</sup> <http://astronomy.nmsu.edu/cwc/Software/irafman/manual.html>

**Table 2**  
AP Col Vital Parameters

AP Col	
Position (J2000 E2000)	06:04:52.16 –34:33:36.0
Astrometric	
$\pi_{\text{rel}}$ (mas)	$118.26 \pm 0.97$
$\pi_{\text{corr}}$ (mas)	$0.95 \pm 0.11$
$\pi_{\text{abs}}$ (mas)	$119.21 \pm 0.98$
Distance (pc)	$8.39 \pm 0.07$
$\mu_{\alpha,\delta}$ (mas yr <sup>-1</sup> )	$(27.33, 340.92) \pm (0.35)$
$\mu$ (mas yr <sup>-1</sup> )	$342.0 \pm 0.5$
P.A. (deg)	$004.6 \pm 0.13$
$V_{\text{tan}}$ (km s <sup>-1</sup> )	$13.60 \pm 0.11$
Photometric	
$V_J$	$12.96 \pm 0.01$
$R_{\text{KC}}$	$11.49 \pm 0.02$
$I_{\text{KC}}$	$9.60 \pm 0.01$
$J_{2\text{MASS}}$	$7.74 \pm 0.03$
$H_{2\text{MASS}}$	$7.18 \pm 0.02$
$K_{s2\text{MASS}}$	$6.87 \pm 0.02$
$M_V$	13.34
$V_J - K_{s2\text{MASS}}$	6.09
$L_x/L_{\text{bol}}$	$-2.95 \pm 0.16$
$\log(L_x)$	$28.49 \pm 17\%$
Variability (mag)	0.017 ( $V_J$ )
Spectroscopic	
Spectral type	M4.5e <sup>a</sup>
Li I $\lambda 6708$ EW (Å)	$0.28 \pm 0.02$
H $\alpha$ EW (Å)	$-9.1 \pm 5.2$ (variable -6 to -35)
$V_{\text{rad}}$ (km s <sup>-1</sup> )	$+22.4 \pm 0.3$
$v \sin i$ (km s <sup>-1</sup> )	$11 \pm 1$
Derived Quantities	
$X$ (pc)	$-3.72 \pm 0.04$
$Y$ (pc)	$-6.70 \pm 0.08$
$Z$ (pc)	$-3.41 \pm 0.04$
$U$ (km s <sup>-1</sup> )	$-21.98 \pm 0.17$
$V$ (km s <sup>-1</sup> )	$-13.58 \pm 0.24$
$W$ (km s <sup>-1</sup> )	$-4.45 \pm 0.13$
Isochronal age (Myr)	12–70
Na I (gravity) age (Myr)	12–100
Li I age (Myr)	12–50

**Note.** <sup>a</sup> Measured type is M4.5Ve, but AP Col is not a main-sequence star.

were reduced with standard IRAF echelle reduction tasks: data are bias-subtracted, then flat-fielded with “wide-decker” flats (flats taken with twice the decker height of the science data). Data are extracted and then wavelength-calibrated with ThAr arclamp spectra. Observational parameters are given in Table 1. The iodine cell was in the light path during the observations of AP Col; as a result, strong iodine absorption features are present from  $\sim 5000$  to  $6000$  Å.

Archival HIRES observations of the M4.5V star GJ 83.1 were retrieved from the Keck Observatory Archive<sup>9</sup> for use in radial velocity cross-correlation. GJ 83.1 has a radial velocity known to be stable to  $<100$  m s<sup>-1</sup> (Nidever et al. 2002). The archival observations from UT 2009 August 10 (PI: Haghighipour) were performed with an identical instrument setup.

<sup>9</sup> <http://www2.keck.hawaii.edu/koa/public/koa.php>

### 3. RESULTS

#### 3.1. Astrometry and Photometry

Based on the *VRI* photometry from CTIOPI, *JHK<sub>s</sub>* photometry from the Two Micron All Sky Survey (2MASS; Cutri et al. 2003) (Table 2), and the photometric distance relations from Henry et al. (2004), we estimate a photometric distance of  $4.6 \pm 0.7$  pc. This is consistent with the spectrophotometric distance estimates from Scholz et al. (2005, 6.1 pc, M5.0e) and Riaz et al. (2006, 4 pc, M5 + H $\alpha$ ).

The astrometric solution for AP Col was calculated using 14 reference stars on 158 *V*-band frames taken over 6.48 yr, from 2004 November to 2011 March. The resulting absolute trigonometric parallax (calculated using the pipeline from Jao et al. 2005) is  $119.21 \pm 0.98$  mas ( $8.39 \pm 0.07$  pc), and the relative proper motion is  $342.0 \pm 0.5$  mas yr<sup>-1</sup> at  $4.6 \pm 0.1$  deg ( $(\mu_{\alpha}, \mu_{\delta}) = (27.33, 340.92) \pm (0.35)$  mas yr<sup>-1</sup>), corresponding to a tangential velocity of  $13.60 \pm 0.11$  km s<sup>-1</sup>; more details are given in Table 2. The trigonometric distance therefore differs from the photometric distance estimate by  $5\sigma$ , putting AP Col  $\sim 1.5$  mag in *V* above the main sequence. This can be caused by youth and/or unresolved multiplicity (see Section 3.3).

There is an issue with the particular *V* filter used between 2005 March and 2009 July (details in Subasavage et al. 2009 and Riedel et al. 2010) that produces a  $\sim 20$  mas false astrometric signal in the R.A. data. An alternative parallax reduction was carried out using only the data from the other, preferred *V* filter and was found to agree with the adopted reduction using all data. We are thus convinced that our parallax and proper motion are accurate, but our ability to detect the presence of companions in our astrometric residuals is thus limited.

#### 3.2. Spectroscopy

Based on our CTIO spectrum, AP Col is an M4.5Ve (accurate to half a subtype) star with substantial H $\alpha$  emission (Table 2). This is confirmed with our WiFeS *B/R3000* spectra, from which we derive a spectral type of M4.5–M5 based on various spectral indices and spectrophotometry.

Each of the Hamilton and WiFeS *R7000* spectra have been cross-correlated with spectra of stars with known radial velocities to derive AP Col’s radial velocity and to search for radial velocity variability between epochs. Each of the Hamilton and WiFeS *R7000* spectra yield radial velocity measurements for AP Col with a precision of roughly 1 km s<sup>-1</sup> and 2 km s<sup>-1</sup>, respectively. Thanks to the use of the iodine absorption cell, we are able to obtain the best precision and accuracy on the HIRES radial velocity measurement (see Table 2), and it is largely responsible for the resulting weighted mean radial velocity.

AP Col’s radial velocity appears stable to 1.3 km s<sup>-1</sup> over 68 days, based on all nine measurements (Table 1). Assuming it is in fact stable, the weighted mean radial velocity is  $+22.4 \pm 0.3$  km s<sup>-1</sup>. Our result is consistent with, but more precise than, the RV reported by Scholz et al. (2005), ( $V_{\text{rad}} = +67 \pm 30$  km s<sup>-1</sup>). This is not surprising considering the low resolution ( $R \simeq 600$ ) of the spectra they used.

AP Col is a known flare star, as reported in Ball & Bromage (1995), and we detected strong H $\alpha$  and numerous other emission lines in its optical spectra (listed in Table 3). Indeed, the Lick and WiFeS *R3000* data show AP Col in the midst of an energetic outburst (H $\alpha$  EW  $\approx 35$  Å). This outburst will be discussed in detail in a future publication (C. Melis et al. 2011, in preparation).

**Table 3**  
Emission Lines Detected in HIRES AP Col Optical Spectra

Transition	Rest Wavelength (Å in air)	EW (Å)
H $\alpha$	6562.852	$-7.3 \pm 0.5$
Na D <sub>1</sub>	5895.924	$-0.4 \pm 0.1^a$
Na D <sub>2</sub>	5889.951	$-1.1 \pm 0.1^a$
He I	5875.621	$-0.8 \pm 0.1^a$
H $\beta$	4861.350	$-8 \pm 1$
He I	4471.480	$-0.3 \pm 0.1$
H $\gamma$	4340.472	$-6 \pm 1$
H $\delta$	4101.734	$-5 \pm 1$
He $\epsilon$	3970.075	$-4 \pm 1$
Ca II H	3968.470	$-10 \pm 2$
Ca II K	3933.660	$-13 \pm 3$
H8	3889.064	$-5 \pm 2$
H9	3835.397	$-4 \pm 2^b$
H10	3797.909	$-0.7 \pm 0.2^b$

**Notes.**

<sup>a</sup> Line contaminated by iodine absorption.

<sup>b</sup> Continuum around line not significantly detected.

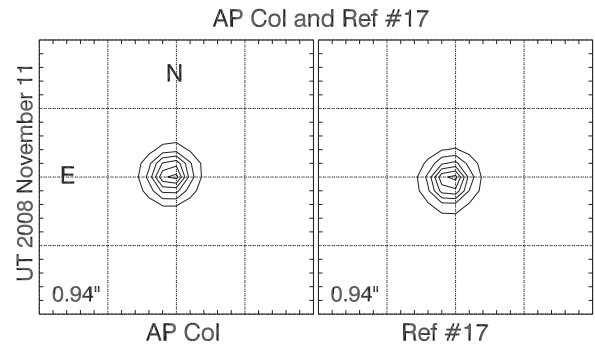
### 3.3. Multiplicity

As determined in Section 3.1, AP Col lies  $\sim 1.5$  mag above the main sequence for a star of spectral type M4.5. Overluminosity can be attributed to at least one of three things: (1) multiplicity (where the brightness of the star is actually the combination of two or more stars), (2) youth (where the star is still gravitationally contracting onto the main sequence), or (3) high metallicity (where the star is not brighter but redder than a typical main-sequence star of the same mass and luminosity much as subdwarfs are bluer than corresponding main-sequence stars).

Given that AP Col lies well above even the high-metallicity envelope of stars within 10 pc, we can reasonably discard the last option. Multiplicity can conspire to make a system appear up to 41% closer as an equal-luminosity binary, or 73% closer as an equal-luminosity trinary. The measured discrepancy, 81%, cannot thus be explained by an equal-luminosity binary, even when the full  $2\sigma$  systematic error on the photometric distance—30%, Henry et al. (2004)—is assumed. If the multiple system is close enough, the stars can tidally interact and force synchronous rotation, which can maintain fast rotational velocities and the resulting chromospheric activity until the system is far older than what is considered “young.”

To address the potential multiplicity of AP Col, we work our way inward. Wide surveys of AP Col on SuperCOSMOS plate scans (Hambly et al. 2001) reveal no wide companions to the star within  $15'$  and brighter than  $\text{SERC}(J) = 21$ ,  $\text{SERC}(I) = 19$ ; within that range only the star 2MASS J06052273-3429245 has noticeable proper motion,  $(-62.38, -119.63) \pm (7.02, 9.95) \text{ mas yr}^{-1}$ , but this proper motion is not similar to AP Col. 2MASS  $JHK_S$  images show no genuine companions down to  $\sim 3''$ ; the apparent close companions are actually “glints,” detector artifacts from internal reflections in the camera.<sup>10</sup>

The highest-resolution seeing-limited image of AP Col from the CTIOPI frames (FWHM  $0''.94$ , taken on UT 2008 November 11) shows no signs of companions to AP Col down to separations of  $0''.9$  and  $\Delta V = 5$ , nor any sign of elongation from an



**Figure 1.** Field immediately surrounding AP Col and the closest reference star, in  $V$  from the CTIO 0.9 m, on a night with good seeing (FWHM =  $0''.94$ ). There is no sign of a companion to AP Col down to  $\Delta V = 5$  mag, or any visible difference between the PSF of AP Col and Ref. 17.

unresolved companion; other images in all three filters show nothing to approximately that limit as well<sup>11</sup> (Figure 1).

Bergfors et al. (2010) Lucky-imaged 124 M dwarfs from the Riaz et al. (2006) sample, including AP Col. Their images, taken in early 2008 November, detected no companions to AP Col at angular separations between  $0''.1$ – $6''.0$  and a magnitude difference of  $\Delta z' \leq 2$  mag at the smallest separations. Independently, B. Mason & W. Hartkopf (2011, private communication) observed AP Col in early 2006 March with the USNO Specklecarn on the CTIO 4 m and also obtained a null result, with  $\Delta \text{vis} \leq 3$  mag at a separation of  $0''.05$ – $1''.0$ .

Further constraints using our CTIO astrometric data are problematic due to the issue with the  $V$  filters mentioned in Section 3.1. While we see no evidence of a companion in the astrometric residuals, we can only constrain the possible multiplicity of AP Col to objects that would produce a photocentric shift smaller than 20 mas in right ascension or 6 mas in declination.<sup>12</sup>

These visual limits, particularly the Lucky and Speckle Imaging, set strict limits on the size of a companion’s orbit. Henry et al. (1999) suggest that an M4.5V main-sequence star has a mass of roughly  $0.25 M_{\odot}$ ; to best explain the overluminosity requires a twin  $0.25 M_{\odot}$  star.<sup>13</sup> With those masses, the longest-period circular orbit that could be hidden within  $0''.05$  (0.42 AU) is 0.38 yr, for which the velocity amplitude would be  $33 \text{ km s}^{-1}$ . We have already established that the radial velocity of AP Col is stable to within  $1.3 \text{ km s}^{-1}$  over the nine epochs and 68 days of RV observations ( $\sim 1/2$  of the maximum orbital period) with cadences as short as one day; this significantly limits the inclinations and eccentricities in which a companion could remain undetected, as shown in Figure 2. Low inclinations can particularly be ruled out given that we have measured the  $v \sin i$  rotational velocity as  $11 \pm 1 \text{ km s}^{-1}$ , which would translate to almost  $300 \text{ km s}^{-1}$  (near break-up speed) if the star’s rotational axis were sufficiently inclined to hide a low-eccentricity orbit. We are thus convinced that AP Col has no stellar-mass companions; substellar companions may still be present but cannot explain AP Col’s elevation above the main sequence. We conclude that the activity and overluminosity we

<sup>11</sup> CTIOPI exposes target stars to roughly the same ADU limit regardless of the filter; the limits in  $\Delta V$ ,  $\Delta R$ , and  $\Delta I$  are thus roughly identical.

<sup>12</sup> Because we are measuring the motion of the photocenter, we are insensitive to equal-mass, equal-luminosity binaries whose photocenter would not shift at all, but we can rule out unequal companions.

<sup>13</sup> As mentioned earlier, additional components would better provide the additional flux, but would necessitate a higher system mass and larger velocity variations.

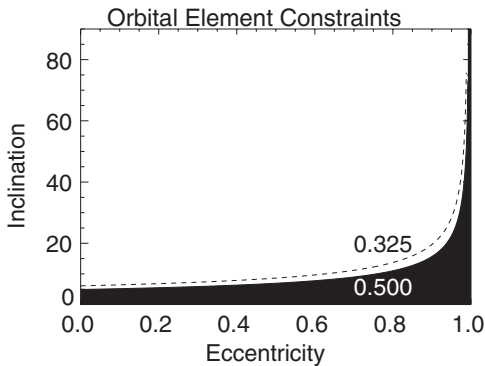
<sup>10</sup> [http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec4\\_7.html](http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec4_7.html)



**Table 4**  
Polynomial Coefficients for Empirical Association Isochrones

Association	No. of Stars in Fit	Min. $V-K$	Max. $V-K$	$c_0$	$c_1$	$c_2$	$c_3$	$c_4$	$c_5$
$\beta$ Pic	32	0.0	6.3	1.6265	2.1789	-0.6631	0.2978	-0.0550	0.00370
TW Hya	16	0.0	8.3	1.4555	0.8992	1.2706	-0.5648	0.0915	-0.00485
AB Dor	41	1.2	5.1	-5.7448	13.6063	-6.5304	1.6629	-0.1949	0.00845
Tuc-Hor	31	-0.6	3.9	1.3926	1.8747	-0.0707	0.4269	-0.2199	0.02960
$\epsilon$ Cha	10	-0.3	6.6	0.4050	1.2320	2.2331	-1.2254	0.2256	-0.01376

**Notes.** Coefficients are for the equation  $M_V = c_0 + c_1(V - K) + c_2(V - K)^2 + c_3(V - K)^3 + c_4(V - K)^4 + c_5(V - K)^5$ .



**Figure 2.** Companion detection limits, given the null results of our companion search down to  $0''.05$  separations, radial velocities stable to  $1.3 \text{ km s}^{-1}$ , and assuming a maximum separation of  $0.42 \text{ AU}$  corresponding to  $0''.05$  at  $8.4 \text{ pc}$ . Below the dashed line, a  $0.075 M_{\odot}$  brown dwarf ( $M_{\text{tot}} = 0.325 M_{\odot}$ ) could be hidden; within the filled region, two  $M4.5V$  stars ( $M_{\text{tot}} = 0.5 M_{\odot}$ , the most likely scenario to explain the overluminosity) could be hidden. Such eccentricities and inclinations are unlikely, and we conclude that AP Col is a single star.

see in AP Col are intrinsic to the star itself (and that it is *not* necessarily a main-sequence star with a mass of  $0.25 M_{\odot}$ ), and not the result of a stellar companion.

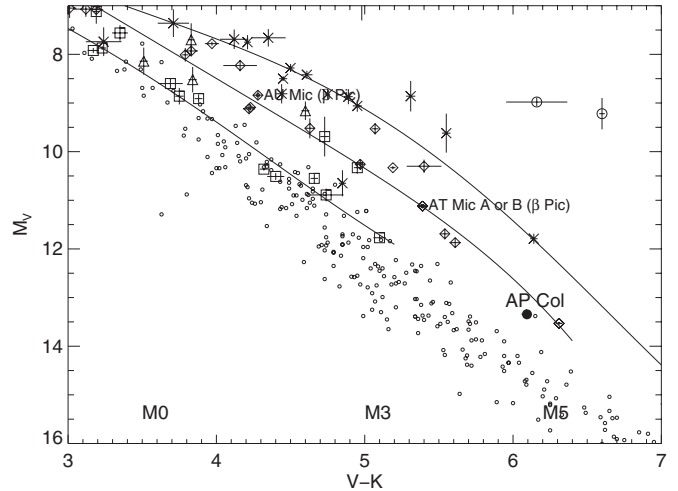
### 3.4. Youth

#### 3.4.1. Isochronal Age

Stars that have not yet reached the main sequence (i.e., equilibrium between gravitational collapse and thermonuclear fusion) will appear overluminous compared to other stars of the same color because their photospheric surfaces are larger than main-sequence stars. Such young stars are therefore elevated relative to the main sequence on an H-R diagram.

To properly compare AP Col to other known young stars without relying on theoretical models requires accurate data. Therefore, we compiled a catalog of known young stars in associations from Zuckerman & Song (2004) and Torres et al. (2008). Position, proper motion, and photometry for each star were extracted from the All Sky Compiled Catalog (Kharchenko 2001), while trigonometric parallaxes<sup>14</sup> were obtained from multiple sources, principally *Hipparcos* (van Leeuwen 2007), the General Catalog of Trigonometric Parallaxes (van Altena et al. 1995), Weinberger et al. (2011), and unpublished data from the CTIOPI observing program. To produce empirical isochrones for nearby associations, multiples, suspected multiples, and obvious outliers (generally noted as such in the *Hipparcos* catalog;

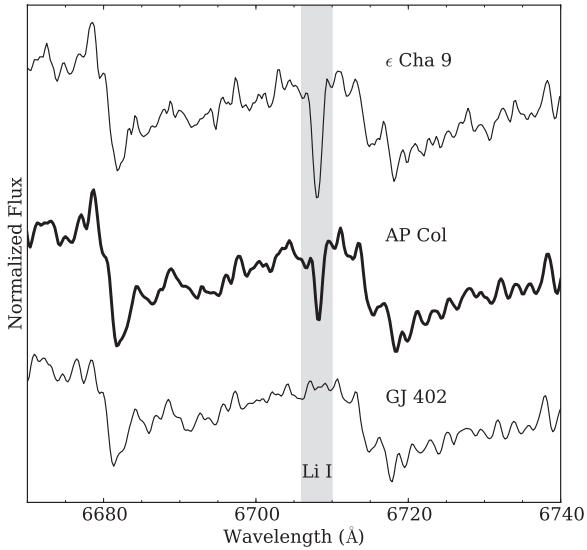
<sup>14</sup> Unlike the general kinematic distances in Zuckerman & Song (2004) and Torres et al. (2008), trigonometric parallaxes are insensitive to any accidental misidentifications with associations. While adding kinematic distances to high-confidence members *would* improve the number of points used in the fits, there are very few known young M dwarfs in these associations.



**Figure 3.** AP Col (filled circle) plotted relative to the RECONS 10 pc sample (the elevated 10 pc object near AP Col is EQ Peg B; see the text), with error bars smaller than the plotted symbol. Also plotted are members of nearby young associations from Zuckerman & Song (2004) and Torres et al. (2008):  $\epsilon$  Cha (large open circles), TW Hya (Xs),  $\beta$  Pic (diamonds), Tuc-Hor (triangles), and AB Dor (squares). Fifth-order fits are plotted for (top to bottom) TW Hya,  $\beta$  Pic, and AB Dor. No attempt has been made to split any unresolved binaries among the associations other than the AT Mic A&B and TWA 22 A&B systems, which both provide overlapping points. AP Col appears to be older than (but consistent with)  $\beta$  Pic, and younger than (but consistent with) AB Dor, although at such red colors and low temperatures, none of the association memberships or isochrone fits are well defined.

Zuckerman & Song 2004 or Torres et al. 2008) were removed from the subset of young stars with parallaxes. The sample was then approximated by fifth-order polynomials to form rough isochrones, which are listed in Table 4.

Figure 3 shows AP Col and the other members of the RECONS 10 pc sample (stars in systems with parallaxes greater than  $100 \text{ mas}$  and errors less than  $10 \text{ mas}$ ; Henry et al. 2006). Known young stars with trigonometric parallaxes are also shown on the graph, along with error bars based on their parallactic and photometric errors (AP Col's errors are smaller than the plotted symbol), and polynomial fits to three of the associations. As the fifth-order polynomials are highly sensitive to the colors of their most extreme members, we have not plotted them past the reddest young star in each association. The  $\epsilon$  Cha isochrone relies on too few points to be reliable, and there are no quality Tucana-Horologium (Tuc-Hor) members cooler than M1 (the single point near AU Mic appears to be a binary). The reddest object in  $\beta$  Pic isochrone is TWA 22AB, originally misclassified as a TW Hya member, with a parallax reported by Teixeira et al. (2009). Only the TW Hya association extends redder than the plot in Figure 3; its reddest member is TWA 27 ( $V - K_S = 8.25$ ,  $M_V = 16.60$ ), with parallaxes in Gizis et al. (2007), Biller & Close (2007), and Ducourant et al. (2008).



**Figure 4.** WiFeS R7000 spectrum of AP Col showing strong lithium absorption ( $\text{Li I } \lambda 6708$ ). The strength of this absorption is intermediate between that of the young ( $\sim 6$  Myr old)  $\epsilon$  Cha member  $\epsilon$  Cha 9 and the older field dwarf GJ 402.

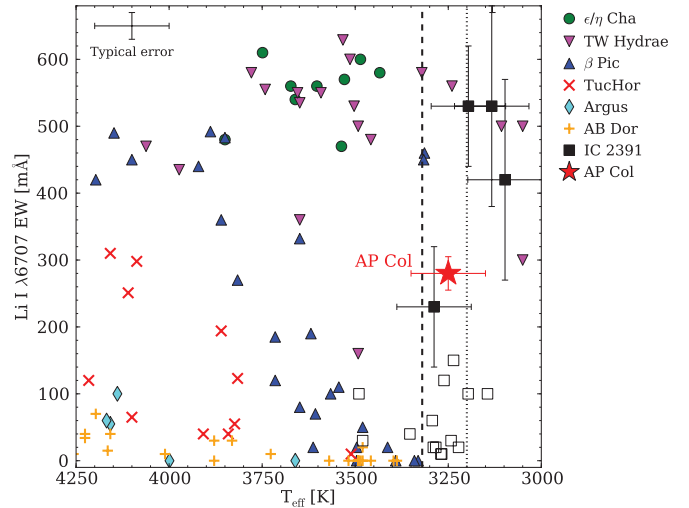
As can be seen in Figure 3, AP Col is clearly older than members of the TW Hya cluster ( $\sim 8$  Myr), and consistent with but likely older than  $\beta$  Pic ( $\sim 12$  Myr). There are no comparably red AB Dor or Tuc-Hor members with known parallaxes; despite this, the position of AB Dor at the high-metallicity upper envelope of the main sequence suggests that AP Col is younger than the  $\sim 70$  Myr AB Dor Association.

### 3.4.2. Lithium

The  $\text{Li I } \lambda 6708$  EW of AP Col is  $0.28 \pm 0.02 \text{ \AA}$ , the weighted mean of all our high-resolution spectral measurements. Lithium is easily destroyed but not readily produced by stellar thermonuclear fusion, and is thus only detected in the photospheres of objects that have not yet consumed their primordial supply of the element. This is usually interpreted as a consequence of youth, or in the case of brown dwarfs, because their cores never reach the temperatures necessary to fuse it. Lithium depletes fastest in mid-M stars, where it is thought that the persistence of full convection throughout the star's evolution to the main sequence means that all the lithium is cycled through the core and quickly destroyed once temperatures rise high enough (Jeffries & Naylor 2001). Larger, hotter stars develop radiative cores that take longer to deplete their lithium and can trap it in their photospheres for a billion years; cooler fully convective stars such as AP Col have longer nuclear burning timescales. Thus, as a coeval stellar population ages, the temperature range of lithium-depleted stars widens around the mid-M stars, with a particularly sharp drop on the cooler side. The detection of lithium in a K- or M-type star is therefore a strong indicator of youth.

By way of comparison, Figure 4 presents WiFeS spectra in the vicinity of the  $\text{Li I } \lambda 6708$  feature for AP Col,  $\epsilon$  Cha 9 (an  $\sim 6$  Myr old member of the  $\epsilon$  Cha Association), and GJ 402 (a field radial velocity standard), all of the same approximate spectral type. The strength of the lithium absorption in AP Col is intermediate between the young  $\epsilon$  Cha member and the old field dwarf, and suggests an intermediate age.

The dependence of lithium burning efficiency on stellar age and temperature leads to the concept of a lithium depletion boundary (LDB), where only a small change in stellar mass and temperature can lead to the appearance or disappearance of the



**Figure 5.**  $\text{Li I } \lambda 6708$  absorption for AP Col (filled star) relative to the young local association members measured by da Silva et al. (2009) ( $\epsilon/\eta$  Cha,  $\sim 6$  Myr; TW Hya,  $\sim 10$  Myr;  $\beta$  Pic,  $\sim 12$  Myr; Tucana-Horologium,  $\sim 30$  Myr; Argus,  $\sim 40$  Myr; AB Dor,  $\sim 70$  Myr). For consistency, all temperatures were calculated from the  $V-I$  color and the transformation of Kenyon & Hartmann (1995). Lower main-sequence members of IC 2391 with  $V-I$  colors from Barrado y Navascués et al. (2004) are also plotted (filled squares; open squares denote upper limits). The decreasing trend in EW with decreasing temperature in the older groups is readily apparent, as are the effects of lithium depletion with age. AP Col is moderately lithium-depleted compared to the younger groups and lies between the  $\beta$  Pic lithium depletion boundary (LDB, dashed line defined by the two systems at  $\sim 3300$  K,  $\text{EW}_{\text{Li I}} \approx 450$  mÅ) and the IC 2391 LDB (approximated by the dotted line). This constrains the age of AP Col to between that of  $\beta$  Pic (12 Myr) and IC 2391 ( $50 \pm 5$  Myr; Barrado y Navascués et al. 2004).

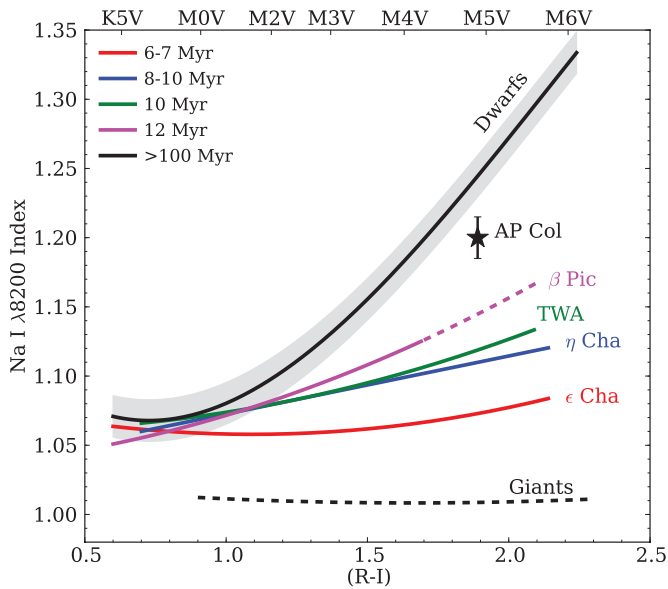
(A color version of this figure is available in the online journal.)

$\text{Li I } \lambda 6708$  feature (Song et al. 2002). For instance, at the age of the  $\beta$  Pic association ( $\sim 12$  Myr), the cool edge of the LDB lies at the spectral type M4.5 (Song et al. 2002; Torres et al. 2003), while at the age of the Pleiades ( $\sim 100$ – $130$  Myr) it has shifted to M6.5 (Stauffer et al. 1998; Barrado y Navascués et al. 2004). While Yee & Jensen (2010), Song et al. (2002) and others have noted that lithium depletion ages are systematically larger than those derived by isochrone fitting or kinematic expansion ages, relative age ranks are not affected.

We plot in Figure 5 the lithium measurements for AP Col, several of the young stellar associations in the solar vicinity from da Silva et al. (2009), and the young cluster IC 2391 from Barrado y Navascués et al. (2004). The  $\beta$  Pic LDB at M4.5 (dashed line) is clearly visible as the discontinuity in EW around 3300 K, while the IC 2391 lithium depletion boundary at  $\sim$ M5 (3200 K) is shown by a dotted line. AP Col lies between the two boundaries at  $T_{\text{eff}} \simeq 3250$  K (based on the  $V-I$  color and the conversion of Kenyon & Hartmann 1995), implying an age between  $\beta$  Pic ( $\sim 12$  Myr) and IC 2391 ( $50 \pm 5$  Myr lithium depletion age; Barrado y Navascués et al. 2004), though consistent with either.

### 3.4.3. Low-gravity Features

Certain spectral features are sensitive to the surface gravity of a star, and may therefore be used as age proxies for stars still contracting toward the main sequence (Hayashi 1966), at least for relative dating (e.g., Lawson et al. 2009). The  $\text{Na I } \lambda 8183/8195$  doublet is particularly useful for comparative gravity studies (e.g., Lawson et al. 2009; Murphy et al. 2010). For spectral types cooler than  $\sim$ M3, there is a marked decrease in



**Figure 6.** Na I index trends for various young, local associations from Lawson et al. (2009). The shaded band represents the variation around the mean dwarf trend seen in Lyo et al. (2004). The value of AP Col has been derived from our WiFeS R3000 spectra, smoothed to the approximate resolution of the Lawson et al. data. The error bar shows the variation observed among the four exposures. AP Col has an intermediate gravity, suggestive of an age between 12 and 100 Myr.

(A color version of this figure is available in the online journal.)

the strength of the Na I doublet between dwarfs (strong), pre-main-sequence stars (intermediate), and giants (weak/absent). To measure the strength of Na I absorption, we adopt the spectral index of Lyo et al. (2004), formed by the ratio of the average flux in two 24 Å wide bands: one on the doublet and the other on the immediately adjacent pseudo-continuum. Figure 6 shows the Na I  $\lambda$ 8200 index for AP Col compared to the mean trends of other young associations in Lawson et al. (2009). To match the resolution used in that study, we have smoothed and resampled the WiFeS R3000 data to  $R \sim 900$  and the same wavelength scale used by Lawson et al. (2009). Although close to the dwarf locus, AP Col nevertheless lies at intermediate gravities between  $\beta$  Pic and field dwarfs; we can again constrain the age to greater than that of  $\beta$  Pic and less than the Pleiades, whose M-type members have gravity features indistinguishable from field stars (Slesnick et al. 2006a).

Alkali metal lines such as Na I can also be affected by stellar activity, where emission fills in the absorption line cores, leading to lower EWs (Reid & Hawley 1999). Our WiFeS observations span a factor of three in  $H\alpha$  EW, but no correlation between that activity indicator and our Na I doublet EW measurements could be found. Slesnick et al. (2006b) note that the Na I  $\lambda$ 8183/8195 doublet can be affected by telluric absorption over the region 8161–8282 Å, leading to artificially low Na I index values for stars observed at large air masses. Our WiFeS R3000 spectra were observed at  $\sec(z) \simeq 1$ ; nevertheless, we have checked the telluric correction of the spectra and find no excess that could affect the index measurements.

#### 3.4.4. $v \sin i$

Young stars are expected to rotate rapidly, with decreasing rotation as they age. Reiners et al. (2009) suggest  $v \sin i > 20 \text{ km s}^{-1}$  is a rapidly rotating M star. From the Keck-I HIRES spectra, we measure a  $v \sin i \sim 11 \pm 1 \text{ km s}^{-1}$ ,

indicating that AP Col is not necessarily a rapidly rotating star. Because it is not in a binary system, this spin is not due to tidal synchronization with a companion; it is a remnant of the star's formation.

While gyrochronology relations exist (e.g., Mamajek 2009) for solar-type stars, none have been developed for M dwarfs, nor stars with saturated X-ray emission such as AP Col. Gyrochronology cannot (yet) be used to estimate an age for AP Col.

#### 3.4.5. Activity: X-ray Emission, $H\alpha$ Emission, Flares, and Photometric Variability

Young stars are known to have large amounts of X-ray emission,  $H\alpha$  emission, flares, and photometric variability, when compared to field stars. All of these indicate chromospheric activity, fast rotation rates, and powerful magnetic fields. This activity also manifests itself photometrically, and young stars have long been recognized for long-term large-amplitude variations and flares since they were first discovered as “Orion-type” variables.

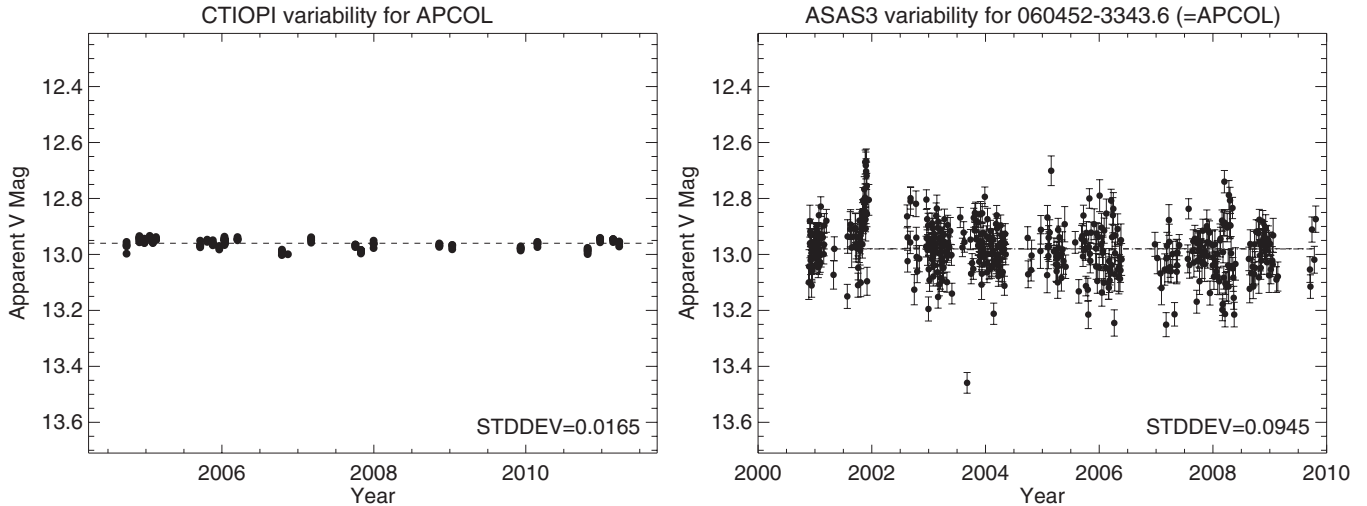
Unfortunately, M dwarfs undergo a long adolescence, and as recognized by Zuckerman & Song (2004) and Hawley et al. (1996), X-rays remain saturated at  $\log(L_x/L_{\text{bol}}) \sim -3$  in M dwarfs past the age of the Hyades ( $\sim 600$  Myr).  $H\alpha$  persists at varying levels for equally long times, and the variability and flaring continues long afterward into the intermediate-age UV Ceti flare stars. Thus, these activity indicators are necessary but insufficient indicators of youth, fairly irrelevant in the face of the measured lithium absorption discussed above, and are discussed mainly for completeness.

AP Col is cross-identified as the *ROSAT* All Sky Survey object 1RXS J060452.1-343331, and has  $\log(L_x/L_{\text{bol}}) = -2.95 \pm 0.16$  and  $\log(L_x) = 28.49$  (17% error). These values match those of Riaz et al. (2006) and agree with the range of X-ray variability published by Scholz et al. (2005),  $\log(L_x/L_{\text{bol}}) = -3$  to  $-4$ .

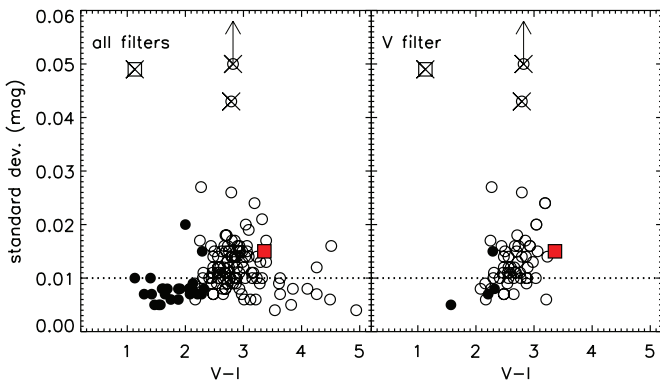
As seen in Table 1, during our spectroscopic observations, the  $H\alpha$  EW of AP Col varied from  $-6$  Å in apparent quiescence, to  $-35$  Å during the strong flare on 2011 January 25, with an average EW of  $-9.1 \pm 5.2$  Å, in agreement with the  $-12.1$  Å single-epoch measurement of Riaz et al. (2006).

AP Col is a known UV Ceti flare star, and Ball & Bromage (1995) observed five flares over nine hours of  $U$ -band observations, the largest of which was 2.5 mag above quiescence. A 12 hr X-ray flare was also measured by *ROSAT* and presented by Scholz et al. (2005); during this event, AP Col increased in X-ray luminosity by roughly an order of magnitude and slowly dropped back to normal levels. We have also measured an energetic white-light flare in Lick Hamilton echelle data taken on 2011 January 25 (C. Melis et al. 2011, in preparation).

Finally, we have measured the relative photometric variability of AP Col using the  $V$ -filter data from the CTIOPI astrometric frames. The standard deviation of the variability is 1.7% (Figure 7). As shown in Figure 8, this is typical when compared to field M dwarfs observed during CTIOPI (Jao et al. 2011). The 158 CTIOPI astrometry frames constitute a total observing time of 14715 s over 27 nights (4 hr, with a median time of 450 s in five observations per night) spanning 6.48 yr. We additionally checked the ASAS3 database (Pojmanski 1997) for photometry on AP Col, and find no evidence of large flares in their data set either (see Figure 7). We report our own variability in Table 2, as our 0.91 m telescope aperture lends itself to better photometry than the 8 cm ASAS telescopes.



**Figure 7.** AP Col relative photometric variability in the  $V$ -filter observations from CTIOPI (left) and ASAS (right). ASAS has lower photometric accuracy than CTIOPI relative photometry. Neither time series shows variability or flares.



**Figure 8.** AP Col (filled square) relative variability as compared to other stars studied during CTIOPI (Jao et al. 2011). Apart from being somewhat redder than other stars observed in the  $V$  filter, AP Col is unremarkable.

(A color version of this figure is available in the online journal.)

### 3.4.6. IR Detection

Young stars often have protostellar disks that show up as near- and mid-IR excesses. These tend to vanish within  $\sim 10$  Myr (Haisch et al. 2001, 2005). *IRAS* and *WISE* photometry from the preliminary data release show no obvious signs of infrared excess around AP Col. This is not unexpected if AP Col is older than  $\sim 10$  Myr, as suggested by our other age indicators.

## 4. CONCLUSIONS

The balance of the age indicators place AP Col somewhere between the ages of  $\beta$  Pic and IC 2391, or  $\sim 12$  Myr to  $\sim 50$  Myr following Torres et al. (2008) and Barrado y Navascués et al. (2004). To give context to the discovery of AP Col, we compare it to the other 255 stellar systems known within 10 pc as of 2011 January 1 (Henry et al. 2006, and updates at [www.recons.org](http://www.recons.org)). As shown in the color–magnitude diagram of Figure 3, AP Col is one of only a few red dwarfs noticeably elevated above the main sequence, with a location of  $M_V = 13.34$ ,  $V-K = 6.09$ .

Three of the elevated points within 10 pc are in one system, comprised of AU Mic, AT Mic A, and AT Mic B (9.9 pc; note that the AT Mic A+B point is actually the overlap of two similar points—the two stars have virtually identical  $V$  and  $K$

magnitudes). This triple is one of the prototypical members of the  $\beta$  Pic association (Barrado y Navascués et al. 1999) with an age of  $\sim 12$  Myr, and is remarkable as the youngest of the 256 systems known within 10 pc.

The elevated point near AP Col in Figure 3 represents GJ 896 B (6.3 pc), also known as EQ Peg B, at  $M_V = 13.38$ ,  $V-K = 6.15$ . Both EQ Peg A and B are known to flare, have  $H\alpha$  in emission, and emit X-rays (Robrade et al. 2004). Both components have also been reported to have companions (Delfosse et al. 1999), but a private communication from the first author of that study indicated that neither spectroscopic companion was confirmed. Thus, we are left with a mystery: the EQ Peg system exhibits some indicators of youth and neither component is known to be multiple, but the A component at  $M_V = 11.24$ ,  $V-K = 4.95$ , is not significantly elevated above the main sequence, while the B component is.

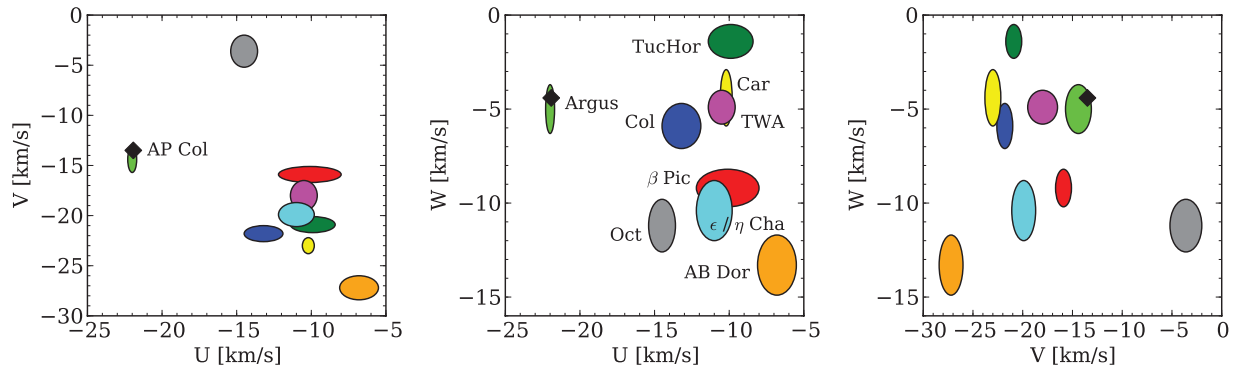
Another potentially young star within 10 pc is GJ 393 (7.1 pc), which Torres et al. (2008) report as a member of AB Dor. However, the star has weak X-ray and NUV emission (Rodríguez et al. 2011), no  $H\alpha$  emission, and slow rotation ( $v \sin i < 3 \text{ km s}^{-1}$ ; Rodríguez et al. 2011), all more typical of older stars. We suspect it is a high-metallicity field star with space velocities coincidentally similar to AB Dor, and note that the AB Dor isochrone happens to lie along the high-metallicity envelope of the main sequence (Figure 3). López-Santiago et al. (2009) also report GJ 393 as an interloping main-sequence star.

Ultimately, the statuses of GJ 393 and GJ 896 AB are still uncertain. AP Col is now the second youngest system within 10 pc, and the closest one, at 8.4 pc from the Sun.

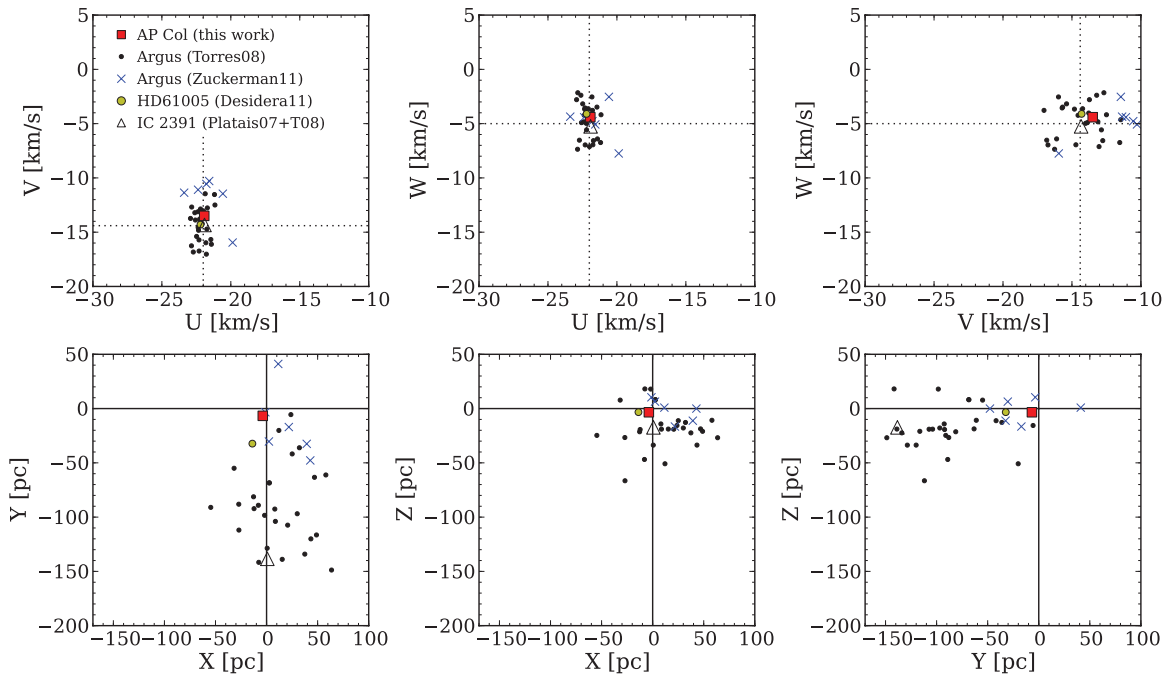
### 4.1. Argus/IC 2391 Membership

One additional point of great interest is that the kinematics of AP Col are an excellent match for the  $\sim 40$  Myr old Argus association defined in Torres et al. (2003) and updated in Torres et al. (2008). Combining the radial velocity with the CTIOPI parallax and proper motion data allows us to calculate the  $UVWXYZ$  phase-space positions for AP Col. These are  $(X, Y, Z) = (-3.72, -6.70, -3.41) \pm (0.04, 0.08, 0.04) \text{ pc}$  and  $(U, V, W) = (-21.98, -13.58, -4.45) \pm (0.17, 0.24, 0.13) \text{ km s}^{-1}$ . This places AP Col only  $1.0 \text{ km s}^{-1}$  from the mean velocity of the Argus association,  $(U, V, W) = (-22.0, -14.4, -5.0) \pm (0.3, 1.3, 1.3) \text{ km s}^{-1}$  (Torres et al. 2008). As seen in Figure 9,





**Figure 9.** AP Col (diamond) plotted in  $UVW$  phase space relative to the associations in Torres et al. (2008). Ellipses show the velocity dispersions of the various groups. Error bars (within the diamond) reflect the accuracy of our measurements. The space motion of AP Col is consistent only with the Argus association. (A color version of this figure is available in the online journal.)



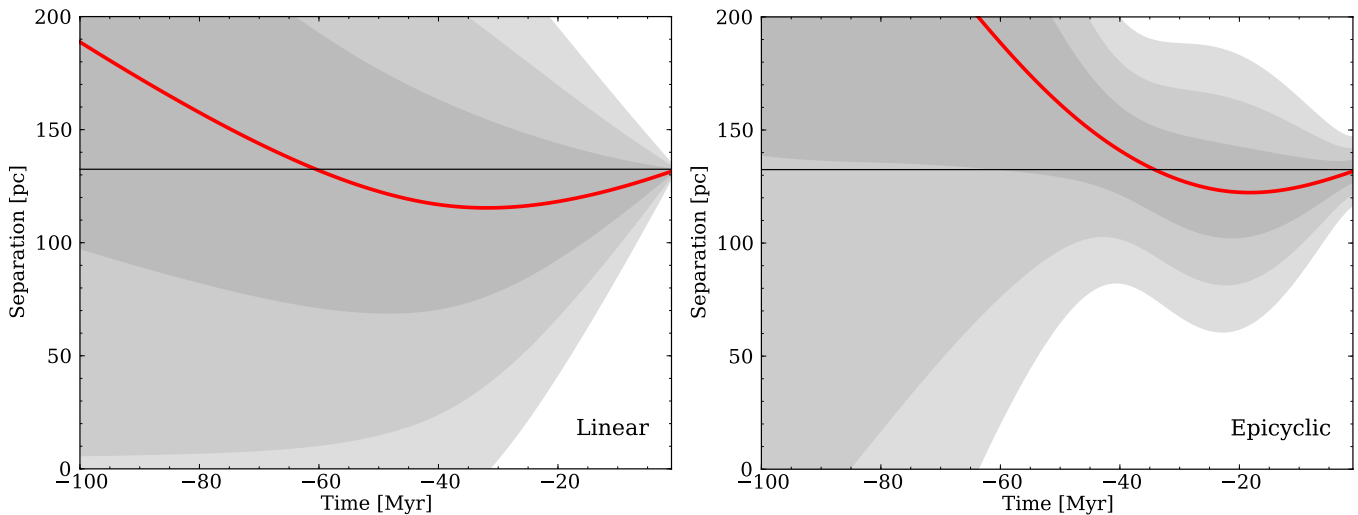
**Figure 10.** AP Col (filled square) plotted in  $UVWXYZ$  phase space relative to the Argus association as defined by Torres et al. (2008; small points). Recent new members found by Desidera et al. (2011; HD 61005, large circle) and Zuckerman et al. (2011; crosses) are also plotted. As shown by Torres et al. (2008), the young open cluster IC 2391 (open triangle; data from Platais et al. 2007; Torres et al. 2008) appears to be kinematically and spatially associated with Argus as well as having a similar age (see the text). (A color version of this figure is available in the online journal.)

Argus is the only possible match for AP Col among the nine nearest known associations, given its observed kinematics. In Figure 10 we plot the phase-space location of AP Col relative to other proposed Argus members from Torres et al. (2008), Desidera et al. (2011), and Zuckerman et al. (2011). In addition to congruent kinematics, AP Col occupies a region of  $XYZ$  space on the outskirts of known members. Argus is likely much larger than the volume traced by known members, and new members continue to be identified. At an age of  $\sim 40$  Myr, Argus also has an isochronal age in the middle of the range expected from our gamut of age indicators.

Although suggestive, kinematics alone are insufficient to argue membership. Unfortunately, there are no previously known M-type Argus members to which we can directly compare AP Col. However, the apparent link between Argus and the young open cluster IC 2391 can provide some insight and reduce the range of possible ages for AP Col.

IC 2391 has similar kinematics (including its “special U velocity”; Torres et al. 2008), spatial location<sup>15</sup> (Figure 10), and a similar age to Argus (Torres et al. 2008; Makarov & Urban 2000). As such, the field members of Argus may be “evaporated” members of IC 2391 stripped free by internal and external interactions with other stars, or distant products of the same filament of gas that eventually became IC 2391. Argus is projected to extend over a huge volume of space, reaching from the center of IC 2391 (distance  $\sim 139 \pm 7$  pc; Torres et al. 2008) to as close as 11 pc (Zuckerman et al. 2011), and, with the discovery and characterization of AP Col, perhaps even 8.4 pc.

<sup>15</sup> IC 2391’s location is shown as derived from 13 Torres et al. (2008) members (drawn from the list of Platais et al. 2007) with *Hipparcos* astrometry. The Torres et al. (2008) distance, 139.5 pc, gives the best kinematic agreement between Argus and IC 2391 but differs from the (Platais et al. 2007) best-fit main-sequence distance of 156 pc. The mean *Hipparcos* distance is between those two values, at 146 pc.



**Figure 11.** Separation between AP Col and the mean IC 2391 location (dotted line) as a function of time, with their current separation ( $\sim 130$  pc) on the right-hand side. Each plot shows the result of 1000 Monte Carlo simulations of the linear/ballistic (left) and epicyclic (right) approximations to Galactic dynamics, using the observed uncertainties in the observed AP Col and IC 2391 space motions. The shaded regions show 1 (darkest), 2, and  $3\sigma$  (lightest) confidence intervals around the mean trend. If AP Col were a member of IC 2391, the separation of AP Col and IC 2391 should go to zero when they were both born ( $\sim 40$ – $50$  Myr ago); they do not reasonably converge at the  $\sim 2\sigma$  level until  $\sim 80$  Myr ago. This implies either interactions have modified the observed velocities, or that AP Col did not form near the core of IC 2391.

(A color version of this figure is available in the online journal.)

Along with their kinematics and spatial positions, the lithium distributions and color–magnitude diagrams of Argus and IC 2391 show good agreement for the solar-type members of the Torres et al. (2008) sample. As already discussed, Figure 5 shows the Barrado y Navascués et al. (2004) IC 2391 members that define the LDB (approximated by the dotted line) at around M5 and an age of  $50 \pm 5$  Myr, subject to the inaccuracies of lithium dating (Yee & Jensen 2010; Song et al. 2002). The position of AP Col in this diagram is consistent with an age similar to that of IC 2391. In fact, the star appears to lie on the LDB, a position supported by the exact agreement of its  $(R - I)$  color and that derived for the LDB by Barrado y Navascués et al. (2004).

In a wider context, da Silva et al. (2009) found that Argus members have a level of lithium depletion between that of the  $\sim 30$  Myr old Tuc–Hor and the  $\sim 70$  Myr old AB Dor associations. This is consistent with the lithium age for IC 2391 above, and our putative age range for AP Col. Thus, given its appropriate kinematics and age, we claim that AP Col, at 8.39 pc, is a likely member of the  $\sim 40$  Myr old Argus association.

One curious piece of evidence contradicts this scenario: if AP Col is an “evaporated” member of Argus/IC 2391, it should converge on the mean location of IC 2391, roughly 40 Myr ago. Using both linear (Murphy et al. 2010) and epicycle (Makarov et al. 2004) approximations to Galactic dynamics to retrace its motion, we find that AP Col does not converge with IC 2391 until (at the very earliest) 80 Myr ago (Figure 11). This result suggests that either the epicycle approximation is insufficient for a 40 Myr traceback, AP Col (and potentially Argus) have been kinematically perturbed since formation (as the evaporated outer envelope of IC 2391), or AP Col (and potentially Argus) formed elsewhere at roughly the same time as IC 2391.

While the evaporation and perturbation scenario can explain our failure to trace AP Col back to IC 2391, it does not explain why, post-interaction(s), the velocity of AP Col is still so close to that of Argus/IC 2391. We instead speculate, like Desidera et al. (2011), that Argus is actually the product of gas surrounding what became IC 2391, thrust into star formation within a few

million years of the cluster, perhaps triggered by supernovae in IC 2391. A similar relationship was suggested by Ortega et al. (2007) in connecting AB Dor with the Pleiades, though we have not connected them in this paper.

In any case, the physicality of Argus is beyond the purpose of this paper; our main conclusion is that, as defined in Torres et al. (2008), AP Col is a member of the Argus association, and is now its closest member. With a presumed age of  $\sim 40$  Myr as part of the Argus association, AP Col is thus the second youngest member of the immediate solar neighborhood, forming during the Eocene epoch on Earth, and at 8.4 pc, the closest star with an age less than 100 Myr.

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