

## OPTICAL DETECTION OF A VARIABLE MILLISECOND PULSAR COMPANION IN 47 TUCANAE<sup>1</sup>

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### ABSTRACT

Using results from radio and X-ray observations of millisecond pulsars in 47 Tucanae, and extensive *Hubble Space Telescope* *U*, *V*, and *I* imaging of the globular cluster core, we have derived a common astrometric solution good to less than 0".1. A close positional coincidence is found for 47 Tuc U, a 4.3 ms pulsar in a 0.429 day orbit, detected in radio and X-rays, with an  $m_V = 20.9$  blue star. Analysis of extensive time series data for this optical candidate shows a 0.004 mag semi-amplitude variation at the period and phase expected from the radio ephemeris, and the optical variations are spatially coincident with the candidate. This provides secure optical detection of the white dwarf companion to the millisecond pulsar, the first such detection in a globular cluster, allowing for comparisons to recent models for such companions with dependencies on mass and age.

*Subject headings:* binaries: general — globular clusters: individual (47 Tucanae) — pulsars: general — pulsars: individual (PSR J0024–7203U)

### 1. INTRODUCTION

The huge improvement in spatial resolution of *Chandra* over previous X-ray missions is proving, like the *Hubble Space Telescope* (*HST*), to have significant impact on globular cluster astrophysics. For example, using *Chandra*, 108 sources have been detected in the central  $2' \times 2.5'$  of the massive globular cluster 47 Tucanae (NGC 104; Grindlay et al. 2001), compared to the detection of nine central sources by *ROSAT* (Verbunt & Hasinger 1998). These *Chandra* sources are a mixture of millisecond pulsars (MSPs), cataclysmic variables (CVs), quiescent low-mass X-ray binaries, and active binaries, many of which have also been detected (P. D. Edmonds et al. 2001, in preparation) in our extensive 8.3 day *HST*/Wide Field Planetary Camera 2 (WFPC2) observations of this cluster (Gilliland et al. 2000). Fifteen of the 20 MSPs detected in 47 Tuc by Camilo et al. (2000) with the Parkes radio telescope have timing positions accurate to  $\leq 0".01$  (Freire et al. 2001, hereafter FCL01), and 10 of these are detected in X-rays with the CIAO program WAVDETECT (errors  $\leq 0".2$ ), allowing for excellent astrometry between the radio and X-ray coordinate frames. Combined with the large numbers of CVs and active binaries detected with both *Chandra* and *HST*, we exploit here the rare opportunity to perform astrometry at the  $\sim 0".1$  level between X-ray, optical, and radio observations, using only relative astrometry.

Of the eight binary MSPs in 47 Tuc with timing solutions (FCL01), five have companions with masses of  $\sim 0.15$ – $0.20 M_\odot$  (Camilo et al. 2000); by analogy with field MSPs, these are expected to be helium white dwarfs (He WDs). Using our precise astrometry, we report here the unambiguous detection of an He WD companion to one of these MSPs (PSR J0024–7203U, hereafter 47 Tuc U), the first such detection in a globular cluster. (He WDs have been reported in the globular cluster NGC 6397 by Cool et al. 1998, Edmonds et al. 1999,

and Taylor et al. 2001, but none of these have yet been associated with an MSP.) The astrometry, photometry, and time series for this identification are described here, along with a discussion of their consequences for the age of 47 Tuc U, the nature of He WDs and their cooling, and the heating effects of an MSP in a close binary.

### 2. OBSERVATIONS AND ANALYSIS

#### 2.1. Astrometry

We assumed the astrometric coordinate system of the MSPs (based on the JPL DE200 planetary ephemeris; FCL01) as our reference. First, we transferred the *Chandra* coordinate frame onto the radio frame using only the relatively isolated MSPs with accurate *Chandra* positions (six MSPs including 47 Tuc U). We calculated and subtracted the mean positional offsets between the X-ray and radio coordinate systems and found the rms residuals were 0".136 and 0".037 for right ascension and declination, respectively (after correcting for small linear correlations between right ascension and right ascension error and declination and declination error). The total error of 0".14 compares favorably with the mean predicted WAVDETECT error, at the relevant count levels and in the absence of background and crowding, of 0".15.

We then fixed the *HST* coordinate system, with positions based on the STSDAS program METRIC, onto that of *Chandra* using the X-ray detection of six CVs and active binaries found on the WF2 chip of the Gilliland et al. (2000) *HST*/WFPC2 data (this chip contains four of the six MSPs, including 47 Tuc U, used to perform the radio to *Chandra* astrometry). The rms residuals were found to be 0".028 and 0".079 for right ascension and declination, respectively. Then, assuming the errors are random and dividing by  $\sqrt{6}$ , the resulting  $1 \sigma$  errors matching X-ray to optical are 0".011 and 0".032 for right ascension and declination, and for radio to optical are 0".057 and 0".049.

Using this astrometry, we searched directly for MSP companions in the *HST* images and found an excellent candidate for a companion to 47 Tuc U (hereafter  $U_{\text{opt}}$ ) whose position is given in Table 1. Finding charts for  $U_{\text{opt}}$  (Fig. 1) show the *U*-band and *V*-band images plus the  $3 \sigma$  error circle for W11 (the *Chandra* X-ray source corresponding to 47 Tuc U) and

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TABLE 1  
POSITIONAL, PHOTOMETRIC, AND TIME SERIES INFORMATION FOR 47 TUC U AND ITS OPTICAL COMPANION  $U_{\text{opt}}$

R.A. (J2000) <sup>a</sup>	Decl. (J2000) <sup>a</sup>	$U$	$V$	$I$	Period ( $V$ ) (days)	$T$ (phase = 0) <sup>b</sup> (MJD)	Amplitude ( $V$ ) (mag)
00 <sup>h</sup> 24 <sup>m</sup> 09 <sup>s</sup> .8325(5)	-72°03'59".667(3)	20.6(1)	20.91(5)	20.70(5)	0.432(4)	51367.32(2)	0.004(1)

<sup>a</sup> Coordinates from FCL01.

<sup>b</sup> Time of optical maximum (see text).

the  $3\sigma$  error ellipse for 47 Tuc U. The offset between W11 and  $U_{\text{opt}}$  is  $0''.055$ , and between 47 Tuc U and  $U_{\text{opt}}$  is  $0''.10$ .

## 2.2. Photometry

Figure 1 shows that  $U_{\text{opt}}$  is clearly blue, since other stars in the  $V$  image of comparable brightness to  $U_{\text{opt}}$  are barely visible in the  $U$  image. This impression is confirmed by our  $V$  versus  $U-V$  and  $V$  versus  $V-I$  color-magnitude diagrams (CMDs) from point-spread function-fitting photometry shown in Figure 2 (we have transformed from *HST* filters to Johnson-Cousins using Holtzman et al. 1995; see also Table 1). The star  $U_{\text{opt}}$  (labeled “U”;  $M_V = 7.47$ ) is blueward of the main sequence (MS) in both CMDs, where the internal error for  $U_{\text{opt}}$  is  $\lesssim 0.03$  mag for each filter, with absolute errors of  $\sim 0.05$  mag in  $V$  and  $I$  and  $\sim 0.1$  mag in  $U$ , including transformation uncertainties. A likely CV is labeled (“1”) as are five blue stars (circles) confirmed by visual examination to be relatively bright in  $U$  like  $U_{\text{opt}}$ . One of these blue stars is probably a CO WD (see Zoccali et al. 2001), two others are variable and likely CO WD-MS binaries, and the other two are possibly also binaries. Visual examination showed that the other apparently blue stars, with  $V < 22$ , are caused by crowding and photometric error, particularly in the crowded portions of the image nearest to the cluster center. Many of the fainter stars with  $V > 22$  and  $0 \leq U-V \leq 1$  are bona fide blue stars, likely to be dominated by MS stars from the SMC (see Zoccali et al. 2001).

The very small number of stars that are blue and detectable in each of  $U$ ,  $V$ , and  $I$  highlights the unusual nature of  $U_{\text{opt}}$  and its likely association with 47 Tuc U. With seven such blue stars, the probability (averaged over the whole WF2 image) of detecting one in a circular aperture of  $0''.15$  radius is only  $9 \times 10^{-5}$ .

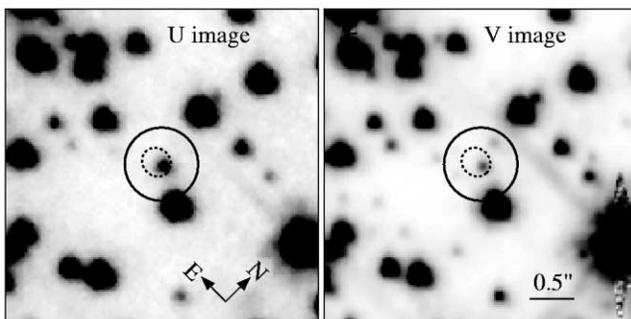


FIG. 1.—Finding chart for 47 Tuc U showing the co-added (over 8.3 days), oversampled images for the  $U$  and  $V$  bands. The solid line shows the  $3\sigma$  error circle (radius =  $3 \times 0''.14$ ) for the X-ray source W11, and the dotted line shows the  $3\sigma$  error ellipse for the radio pulsar 47 Tuc U, after accounting for the transformation between radio and optical frames and assuming random errors. The optically detected binary companion to 47 Tuc U ( $U_{\text{opt}}$ ) is near the center of the W11 error circle.

## 2.3. Time Series

The *HST*/WFPC2 data of Gilliland et al. (2000) contain 636  $V$ -band and 653  $I$ -band 160 s images evenly spread over 8.3 days. Typical rms noise values in fractional intensity (Gilliland et al. 2000) are  $\sim 0.003$  at  $V = 17$  and  $\sim 0.013$  at  $V = 20$ . Since  $U_{\text{opt}}$  is relatively well isolated, the quality of its  $V$  and  $I$  time series, based on its extracted aperture of  $0''.34$ , is excellent. Its rms noise values are 0.021 ( $V$ ) and 0.034 ( $I$ ), or  $-0.1\sigma$  and  $0.6\sigma$  away from the mean rms values for the 666 ( $V$ ) or 551 ( $I$ ) stars within 0.25 mag of  $U_{\text{opt}}$ , after iteratively removing greater than  $3\sigma$  outliers.

We then searched for evidence of low-amplitude variations in  $U_{\text{opt}}$ . Lomb-Scargle (Scargle 1982) power spectra of the  $V$  and  $I$  time series for 47 Tuc U are shown in the upper panel of Figure 3. This shows a peak in the  $V$  band, at  $(2.681 \pm 0.07) \times 10^{-5}$  Hz, which is coincident with the orbital period for 47 Tuc U ( $2.697 \times 10^{-5}$  Hz) determined from radio observations. Although this peak is not statistically significant in a blind search, only one other peak, when measured out to 0.45 mHz (the “average” Nyquist frequency; Scargle 1982), has a higher signal. No corresponding signal is seen in the  $I$  band.

We then carried out a least-squares fit of a sinusoid to the time series, by coordinating the radio ephemeris with the optical and correcting the midexposure *HST* times to the barycenter,

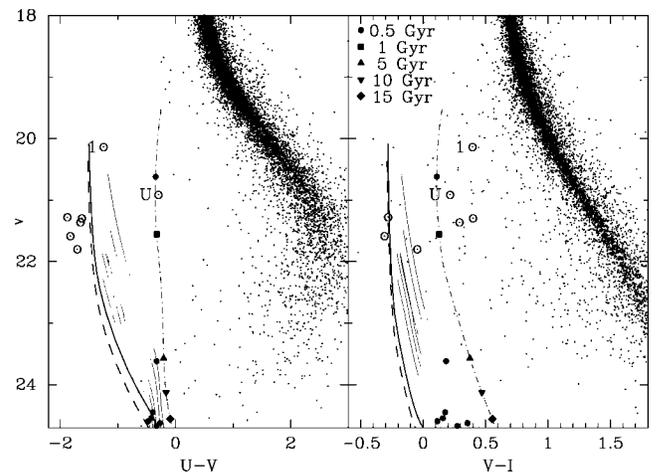


FIG. 2.— $V$  vs.  $U-V$  and  $V$  vs.  $V-I$  CMDs for the WF2 chip. The 47 Tuc U MSP companion  $U_{\text{opt}}$  is denoted by “U,” a CV by “1,” and other blue stars by circles. The position of  $U_{\text{opt}}$  is slightly redder and brighter than those of the He WDs in NGC 6397 reported in Cool et al. (1998). The thicker lines show Bergeron et al. (1995) models for  $0.5 M_{\odot}$  (solid line) and  $0.6 M_{\odot}$  (dashed line) CO WDs. The thinner lines are SAR01 models, for He WD masses of 0.406, 0.360, 0.327, 0.292, 0.242, and  $0.196 M_{\odot}$ , with mass decreasing toward the red, and  $0.169 M_{\odot}$  (dot-dashed line). Cooling ages are as shown. These models have been plotted assuming that  $(m-M)_0 = 13.27$ , the mean of the nine distance modulus values reported in Zoccali et al. (2001),  $E(B-V) = 0.055$  (Zoccali et al. 2001),  $A_I/A_V = 1.51$ , and  $A_I/A_V = 0.60$  (Holtzman et al. 1995). Using  $(m-M)_0 = 13.27$ , the 47 Tuc distance is 4.5 kpc.

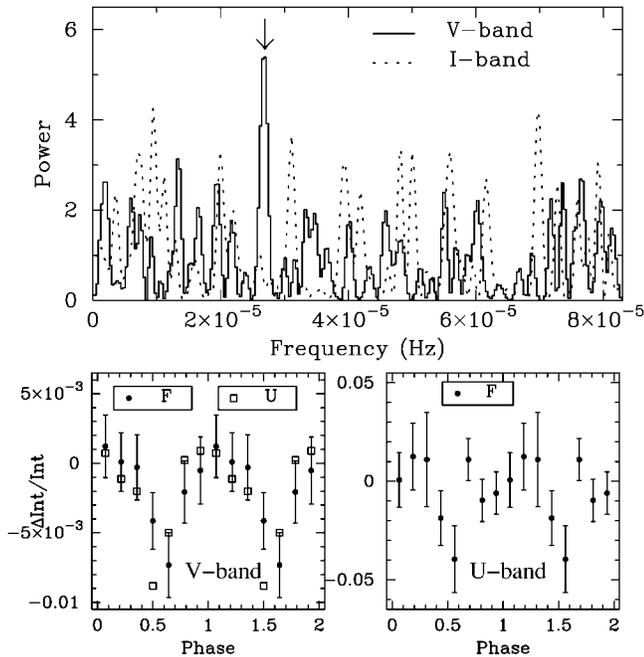


Fig. 3.—Power spectra and phase plots for  $U_{\text{opt}}$ . The upper panel shows power spectra (V and I bands, as labeled) for  $U_{\text{opt}}$ , with power shown in Lomb-Scargle units (Scargle 1982). The binary frequency of 47 Tuc U measured from radio observations is indicated with an arrow. The lower panels show phase plots for the V- and U-band data for  $U_{\text{opt}}$ , where fractional intensities are plotted and the errors are from the time series rms values scaled by the square root of the number of points in each bin. “F” denotes the forced fit, and “U” the unforced fit (see § 2.3 for a description). The point near phase 0.5 in the U-band data is formally only significant at the 2.3  $\sigma$  level. No evidence is found for variation in the I band, and so the phase plot is not shown here.

using the IRAF task RVCORRECT. We define phase =  $[T - (T_{\text{asc}} - P/4)]/P$  (where  $T$  is the barycentric time,  $T_{\text{asc}}$  is the time of ascending node, when the pulsar is moving with maximum velocity away from us, and  $P$  is its orbital period) so that when phase = 0.0 the heated hemisphere of  $U_{\text{opt}}$  is facing toward us, giving maximum light (in a model where  $U_{\text{opt}}$  is heated by the pulsar wind). The derived period, time of optical maximum (phase = 0), and semi-amplitude for the V-band time series are given in Table 1 (V phase plots are shown in the lower left panel of Fig. 3). For the “unforced” solution, the period is 0.7  $\sigma$  away from the orbital radio period, and the phase is 1.9  $\sigma$  away from phase zero for the radio observations (as defined above). The amplitude is significant at the 3.4  $\sigma$  level (the significance of this measurement is  $>3.4 \sigma$  when the  $\sim 1/10$  chance probability of the radio and optical phases aligning is considered). By forcing the period and phase of the sinusoidal variation to equal the radio values (the “forced” solution), an amplitude of  $0.0033 \pm 0.0012$  is derived, significant at the 2.8  $\sigma$  level; a forced fit in the I band yielded  $0.0013 \pm 0.0018$ . Marginal evidence is found for variation in the much more limited (26 images of length 160–900 s) U-band data (see Fig. 3).

To test whether this small variation in V is intrinsic to  $U_{\text{opt}}$  rather than a larger variation from a nearby fainter star, we examined the power spectra of three fainter stars (with  $V \geq 22$ ) lying within  $\sim 0.5'$  of  $U_{\text{opt}}$ . None showed significant variations. We also examined a “phase difference” image derived by adding together images where the phase of  $U_{\text{opt}}$  is within 0.07 of 1.0 and subtracting similar images for phase

values of  $0.5 \pm 0.07$ . This procedure gave a stellar-shaped source coincident, at the 0.5 pixel ( $0.05''$ ) error level, with  $U_{\text{opt}}$ , exactly as expected if  $U_{\text{opt}}$  is the only star varying with the radio period and phase. We therefore conclude we have made a solid detection of variability from  $U_{\text{opt}}$  at the expected period and phase, confirming it as the 47 Tuc U companion.

### 3. DISCUSSION

Neutron stars (NSs) in binary radio pulsar systems have average masses of  $M_{\text{NS}} = 1.35 \pm 0.05 M_{\odot}$  (Thorsett & Chakrabarty 1999). For 47 Tuc U, considering a NS mass  $1.30 M_{\odot}$  and an edge-on orbit (inclination  $i = 90^{\circ}$ ), we derive from the mass function a minimum mass for  $U_{\text{opt}}$  of  $M_U = 0.120 M_{\odot}$ . This 4.3 ms pulsar has an approximate characteristic age of  $\tau \sim 2$  Gyr and spin-down luminosity of  $\dot{E} \sim 2 \times 10^{34}$  ergs  $\text{s}^{-1}$  (J. E. Grindlay et al. 2001, in preparation). Such recycled pulsars may have accreted significant amounts of mass, and for every additional  $0.05 M_{\odot}$  for the NS,  $M_U$ 's minimum value increases by  $0.003 M_{\odot}$ .

We now compare the U, V, and I colors of  $U_{\text{opt}}$  with expectations from H and He WD models to test whether it is a plausible He WD and if so, to estimate  $T_{\text{eff}}$ ,  $\log g$ , and the mass and age of this star. We focus on comparisons with the models of Serenelli et al. (2001, hereafter SAR01), who conveniently provide broadband color information. They find that for masses ranging from 0.18 to  $0.41 M_{\odot}$ , diffusion-induced hydrogen-shell flashes take place, which deplete the H envelope and cause evolution to proceed relatively quickly, while the He WDs with mass less than  $0.18 M_{\odot}$  evolve much more slowly because they retain relatively thick hydrogen envelopes. Althaus, Serenelli, & Benvenuto (2001) and SAR01 show that this dichotomy between low- and high-mass He WDs removes the discrepancies between MSP characteristic ages and WD cooling ages for several field systems including PSRs J0034–0534, J1012+5307, J1713+0747, and B1855+09.

Figure 2 shows the He WD cooling curves of SAR01 for masses of 0.169– $0.406 M_{\odot}$ . Since  $U_{\text{opt}}$  lies well to the red of the WD cooling sequence of Bergeron, Wesemael, & Beauchamp (1995) in both CMDs, it is unlikely to be an  $\sim 0.55 M_{\odot}$  CO WD. The lowest mass models of SAR01 offer much better agreement, and since  $U_{\text{opt}}$  falls slightly to the red of the lowest mass sequence, we infer that  $M_U \lesssim 0.17 M_{\odot}$  (implying  $i \geq 45^{\circ}$ ). This would mean that 47 Tuc U is similar to the field system PSR J1012+5307, with a period of 0.605 days and mass  $\sim 0.16 M_{\odot}$  (Callanan, Garnavich, & Koester 1998).

The  $0.17 M_{\odot}$  SAR01 model with the same absolute magnitude as  $U_{\text{opt}}$  has  $T_{\text{eff}} = 11,000$  K,  $\log g = 5.6$ , a luminosity equal to  $0.14 L_{\odot}$ , a radius<sup>5</sup> of  $\sim 7.3 \times 10^9$  cm, and an age of  $\sim 0.6$  Gyr. This cooling age is somewhat less than the characteristic age estimated by J. E. Grindlay et al. (2001, in preparation) and is at the low end of the conservative limits set by FCL01 of  $0.4 < \tau < 4.2$  Gyr. Only the lowest mass model of SAR01 remains relatively bright at these significant cooling ages, while all of the higher mass WDs reach much fainter levels ( $M_V \sim 12$ ) at a cooling age of  $\sim 1$  Gyr (see Fig. 2). Our data therefore provide tentative support for the evolutionary calculations of SAR01, in particular for the dichotomy in ages between different

<sup>5</sup> The estimated radius is fairly insensitive to the details of the SAR01 WD models, since  $T_{\text{eff}}$  can be estimated accurately just from the V–I color (Hansen & Phinney 1998) and the luminosity using only the V magnitude and  $T_{\text{eff}}$ .

mass He WDs. For comparison, the He WD models of Hansen & Phinney (1998) (for all masses) reach  $M_i = 11.5$  or fainter after 1 Gyr, for a relatively thick hydrogen envelope of  $3 \times 10^{-4} M_\odot$ .

Accretion should have ceased in the 47 Tuc U system, to explain the faint X-ray luminosity ( $2 \times 10^{30}$  ergs s $^{-1}$ ; J. E. Grindlay et al. 2001, in preparation) and the constant, unclipped radio emission (FCL01). Using the Roche lobe formula from Paczyński (1971;  $r/a = 0.462[(M_U/(M_{NS} + M_U))]^{1/3}$ , where  $r$  is the Roche lobe radius and  $a$  is the binary separation), the WD radius given above (for  $M_U = 0.17 M_\odot$ ;  $i = 45^\circ$ ), and the binary separation from Kepler's third law,  $U_{opt}$  should underfill its Roche lobe by a factor of  $\sim 6$ . Therefore, as expected, no accretion will be occurring.

Assuming that the MSP radiates its wind isotropically, and that  $i = 45^\circ$ , then the  $\dot{E}$  estimate implies that the pulsar energy intercepted by  $U_{opt}$  should be  $\sim 7 \times 10^{30}$  ergs s $^{-1}$  or 0.013 times the luminosity of  $U_{opt}$  (assuming that the spin-down energy is reradiated as a blackbody, we expect the temperature of  $U_{opt}$  to rise by only  $\sim 35$  K). Therefore, assuming that only one side of  $U_{opt}$  is heated, we should see a relative variability amplitude of  $\sim 0.005$ , allowing a factor of 1.4 decrease in possible amplitude because of the inclination. This is only slightly larger than the amplitude of the detected  $V$ -band variation, implying a high efficiency factor for reradiation of the pulsar's wind as optical emission. However, because the variability expected from the effects of heating is small, we infer that the possible ( $2.3 \sigma$ ) much larger amplitude variation in the  $U$  band is either spurious or evidence for a separate source of emission.

#### 4. SUMMARY AND FOLLOW-UP OBSERVATIONS

We have identified the binary pulsar 47 Tuc U with an optically variable blue star with period and phase of maximum light in excellent agreement with that expected from the precise radio ephemeris (FCL01). The companion is likely to be an He white dwarf with  $M_U \lesssim 0.17 M_\odot$ , based on the published models of SAR01.

Although the optical time series photometry reported here is unlikely to be improved upon soon, time-resolved spectroscopy with *HST*/Space Telescope Imaging Spectrograph of  $U_{opt}$  appears promising. The co-added Doppler-corrected spectrum could be used to spectroscopically determine  $T_{eff}$  and  $\log g$ , and hence  $M_U$  (see, e.g., Edmonds et al. 1999). Combining  $M_U$  with the radial velocity amplitude of  $U_{opt}$  ( $K_U$ ) and the measured  $K_{NS}$  from the radio measurements would give a direct measurement of  $M_{NS}$ .

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