DISCOVERY OF PULSATIONS IN THE X-RAY TRANSIENT 4U 1901+03

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Accepted by ApJ

ABSTRACT

We describe observations of the 2003 outburst of the hard-spectrum X-ray transient 4U 1901+03 with the Rossi X-ray Timing Explorer. The outburst was first detected in 2003 February by the All-Sky Monitor, and reached a peak 2.5–25 keV flux of $8 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ (around 240 mCrab). The only other known outburst occurred 32.2 yr earlier, likely the longest presently known recurrence time for any X-ray transient. Proportional Counter Array (PCA) observations over the 5-month duration of the 2003 outburst revealed a 2.763 s pulsar in a 22.58 d orbit. The detection of pulsations down to a flux of $3 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ (2.5–25 keV), along with the inferred long-term accretion rate of $8.1 \times 10^{-11}$ M$_\odot$ yr$^{-1}$ (assuming a distance of 10 kpc) suggests that the surface magnetic field strength is below $\sim 5 \times 10^{11}$ G. The corresponding cyclotron energy is thus below 4 keV, consistent with the non-detection of resonance features at high energies. Although we could not unambiguously identify the optical counterpart, the lack of a bright IR candidate within the 1$'$ RXTE error circle rules out a supergiant mass donor. The neutron star in 4U 1901+03 probably accretes from the wind of a main-sequence O-B star, like most other high-mass binary X-ray pulsars. The almost circular orbit ($e = 0.036$) confirms the system’s membership in a growing class of wide, low-eccentricity systems in which the neutron stars may have received much smaller kicks as a result of their natal supernova explosions.

Subject headings: accretion — pulsars: general — pulsars: individual (4U 1901+03) — X-rays: stars

1. INTRODUCTION

More than half of the known X-ray pulsars are transient sources which were discovered during bright outbursts. Most of these are Be-star/X-ray binaries, which are believed to be progenitors of double neutron star binaries (e.g. Bhattacharya & van den Heuvel 1991). In contrast to binaries with low-mass ($\lesssim 1$ M$_\odot$) companions, the neutron stars in these high-mass X-ray binaries (HMXBs) typically accrete through the companion’s stellar wind. The mass transfer rate $\dot{M}$ — as well as its variability — depends in a sensitive manner on the wind properties, as well as on the neutron star spin period and magnetic field strength. A smaller class of pulsars accrete from supergiant companions, which may fill their Roche lobes and thus accrete persistently. Tidal forces in these binaries act to circularize the orbits on a time scale much shorter than the active lifetime, while the wider, wind-accreting binaries typically have moderate to high eccentricities (e.g. Bildsten et al. 1997). In recent years, a third class of binaries has emerged, with wide $\gtrsim 20$ d orbits but low eccentricities $e \lesssim 0.1$. These sources present difficulties for the commonly accepted formation scenario in which the natal supernova event imparts a “kick” to the neutron star, leading to an initially eccentric orbit. The tidal forces which act so efficiently in the Roche-lobe filling systems cannot circularize wider orbits within the source lifetime, suggesting that the initial kicks in these wide, circular binaries may be unusually small (Pfahl et al. 2002).

For some transients the interval between outbursts can be as long as 20 yr. Little is generally known about sources with such long duty cycles, due to the dearth of observations (in particular with large-area modern instruments with good timing capabilities). For some candidate X-ray pulsars no pulsations have even been detected, and the classification comes from a hard X-ray spectrum, typical in confirmed pulsars. 4U 1901+03 ($i = 37\degree16$, $b = -1\degree25$) is such a source, previously detected just once before in outburst by Uhuru and Vela 5B in 1970–1 (Forman et al. 1976; Friedhorsky & Terrell 1984). Due to the hard spectrum measured during those observations, the source was tentatively identified as an HXB. Consequently, we selected this source as one of a group of hard transients with positions known to 10$'$ or better, as candidates for target-of-opportunity observations by the Rossi X-ray Timing Explorer (RXTE). In 2003 February a new outburst of 4U 1901+03 was detected by the All-Sky Monitor (ASM) aboard RXTE (Galloway et al. 2003). The source was also detected with the IBIS and JEM-X hard X-ray instruments aboard INTEGRAL between 2003 March 10 and April 13 2003 (Molkov et al. 2003). An RXTE Proportional Counter Array (PCA) scan across the Uhuru position led to more precise coordinates of R.A. = $19\text{h}03\text{m}37\text{s}$, decl. = $+3\degree11\arcmin31\arcsec$ (J2000.0), with an estimated 90% confidence uncertainty of 1$''$ (Galloway et al. 2003). Follow-up pointed RXTE observations detected coherent pulsations with a period of 2.763 s. Variations in the observed pulse frequency were also observed, suggesting an orbital period of around 25 d.

Here we present timing and spectral analyses of RXTE observations of 4U 1901+03 throughout the 2003 outburst, as well as results from a search for the optical/IR counterpart.
2. OBSERVATIONS

We made observations of 4U 1901+03 with the Proportional Counter Array (PCA; Jahoda et al. 1996) and the High-Energy X-ray Timing Experiment (HEXTE; Gruber et al. 1996) instruments aboard RXTE. The PCA consists of 5 Proportional Counter Units (PCUs) each with a collecting area of \(\approx 1400 \text{ cm}^2\) and a 1° field of view, that are sensitive to X-ray photons with energies in the range 2.5–90 keV. Photon arrival times are measured to \(\approx 1 \mu s\), while spectra are accumulated in up to 256 energy channels. The HEXTE comprises two clusters, each with 4 scintillation detectors sensitive to photons in the range 15–250 keV, collimated to view a common 1° field. The detectors in the two clusters provide a total collecting area of 1600 cm\(^2\).

Short (\(\approx 3 \text{ ks}\)) observations were scheduled every 3–4 days between 2003 February 10 and July 16 (MJD 52,680 and 52,837) in order to adequately sample the 25 d candidate orbital period. In addition, several longer observations were scheduled near the peak of the outburst as part of a separate proposal to search for cyclotron resonance features (PI: Heindl). Data were analysed using lheasoft release 5.3 (2003 November 17). We extracted PCA and HEXTE spectra from intervals within each observation during which the center of the field-of-view was within 0.02° of the position of 4U 1901+03, and for which the limb of the Earth was more than 10° from the source direction. Spectra were extracted from standard observing mode data for each instrument (“Standard-2”, with 129 channels between 2–60 keV for the PCA, and “Archive”, with 64 channels between 15–250 keV for the HEXTE). PCA spectra were accumulated separately for each PCU, and instrument response matrices were generated for each PCU and each observation using pcarsp v.10.1. We estimated background count spectra for the PCA using “bright” source models (suitable for when the count rate exceeds \(\approx 40 \text{ counts s}^{-1} \text{ PCU}^{-1}\)) developed for gain epoch 5 (2000 May 13 onwards) with pcabackest. We measured the mean flux for each observation by fitting spectra from individual PCUs separately (using the model described in §4) between 2.5–25 keV\(^2\). We corrected the integrated 2.5–25 keV flux (except for PCU 2) by dividing by the mean ratio of the fluxes for each PCU relative to PCU 2, and adopted the residual standard deviation on the rescaled fluxes as the 1σ uncertainty. For our timing analysis we used full-range PCA lightcurves with 4 ms time resolution, with time bins corrected to the solar system barycenter.

3. RESULTS

3.1. Flux evolution and X-ray spectrum

The X-ray flux peaked at almost \(8 \times 10^{-9} \text{ ergs cm}^{-2} \text{s}^{-1}\) (2.5–25 keV; approximately 240 mCrab) around 2003 February 20 (MJD 52,690) and decreased linearly down to \(\lesssim 10^{-10} \text{ ergs cm}^{-2} \text{s}^{-1}\) by 2003 July 15 (Fig. 1). Although bright outbursts in transient pulsars are sometimes followed by extended periods of lower-level activity (e.g. KS 1947+300; Galloway et al. 2004), the ASM did not detect 4U 1901+03 at a significant level between the end of the 2003 outburst through 2005 June. The modest PCA energy resolution at low energies meant that it was not possible to constrain the column density \(n_H\) for neutral absorption in the spectral fits. Thus, for all our spectral fits we froze \(n_H\) at 1.2 \times 10^{22} \text{ cm}^{-2}\) (at the lower end of the expected range inferred from the AV estimates; see §2). We found the best agreement with the data for a model consisting of a Comptonisation component (comptt in xspec; Titarchuk 1994) and a Gaussian component centered around 6.4 keV to represent fluorescent Fe line emission, both attenuated by neutral absorption with column density at the survey value. We assumed a systematic error of 1% in order to achieve a reduced \(\chi^2\) of \(\approx 1\). A systematic error of this magnitude is typically required for PCA spectral fits to bright sources, for example the Crab pulsar (R. Remillard, pers. comm.).

Near the end of the outburst (between MJD 52,780 and 52,820) the reduced-\(\chi^2\) was somewhat larger, between 2 and 3.5. The main factor contributing to the poor \(\chi^2\) value was a deficit of photons (compared to the model) between 8 and 10 keV; this deficit was observed irrespective of the choice of continuum components tested. In low signal-to-noise spectra (e.g. from short observations), the residuals could be removed by including a blackbody component with \(kT_{bb} \approx 1 \text{ keV}\), but for longer observations the residuals were more complex. Although the residuals indicate that the adopted spectral model does not completely describe the source spectrum, the derived parameters present a qualitative description that is adequate for flux measurements as well as a general characterisation of the spectral shape and its

\(^2\) The Crab flux in this energy range is \(3.3 \times 10^{-8} \text{ ergs cm}^{-2} \text{s}^{-1}\).
indicated systematic deviations at energies outburst (Fig. 2). Although the best-fit residuals still in-spectrum hardened considerably over the course of the evolution of the Comptonisation model parameters, the spectrum was rather soft for a HMXB pulsar, with fits were similar to the fits to the PCA data only. The outburst. The spectral parameters for these broadband tra for selected observations near the peak and end of the variation. The fitted optical depth $\tau$ decreased slightly over the course of the outburst, from 6 at the peak to 4 near the end of the outburst. The temperature of the scattering electrons $kT_e$ increased over the same period from 4 to 7 keV. A narrow emission feature around 6.4 keV was present throughout, with equivalent width between 60 and 150 eV.

We also made combined fits to PCA and HEXTE spectra for selected observations near the peak and end of the outburst. The spectral parameters for these broadband fits were similar to the fits to the PCA data only. The spectrum was rather soft for a HMXB pulsar, with little emission detected above 80 keV. As indicated by the evolution of the Comptonisation model parameters, the spectrum hardened considerably over the course of the outburst (Fig. 2). Although the best-fit residuals still indicated systematic deviations at energies $< 10$ keV from the best-fit model spectrum, we found no evidence for cyclotron resonance features in the spectrum. Using the broadband fits, we estimated the bolometric correction as the ratio of fluxes integrated over an idealised response matrix spanning 0.1–200 keV, and the flux in the range 2.5–25 keV, as 1.12.

3.2. Pulse timing

We estimated the pulse frequency for each observation by first folding the 4-ns lightcurve on a trial period, to obtain an observation-averaged pulse profile with (typically) 32 phase bins. We then folded individually 256-s segments on the same period, and cross-correlated the resulting pulse profiles with the observation-averaged profile to obtain the phase delay for each segment. We then adjusted the period and repeated the procedure until the phase delay exhibited no net trend with time throughout the observation. The error was estimated from the uncertainty on the first-order term of a linear fit to the phase delays. The resulting frequency history shows approximately sinusoidal variations indicative of Doppler shifts from binary orbital motion, superimposed on a significant (non-linear) spin-up trend over the course of the outburst (Fig. 3).

We fit the frequency measurements with a linear model comprising the spin-up due to accretion torques in addition to the apparent changes due to orbital Doppler shifts:

$$f(t) = f_{\text{spin}}(t) - \frac{2\pi f_0 a_X \sin i}{P_{\text{orb}}} \times (\cos l + g \sin 2l + h \cos 2l)$$

(1)

where $f_{\text{spin}}(t)$ is the time-dependent neutron-star spin frequency, $f_0$ is a constant approximating $f_{\text{spin}}(t)$, $a_X \sin i$ is the projected orbital semimajor axis in units of light travel time, and $P_{\text{orb}}$ is the orbital period. The coefficients $g (= e \sin \omega)$ and $h (= e \cos \omega)$ are functions of the eccentricity $e$ and the longitude of periastron $\omega$. Finally, $l = 2\pi (t - T_{\pi/2})/P_{\text{orb}} + \pi/2$ is the mean longitude, with $T_{\pi/2}$ the epoch at which the mean longitude $l = \pi/2$. For a circular orbit, $T_{\pi/2}$ is the epoch of superior conjunction (when the neutron star is behind the companion). The right-most term in Eqn. 2 represents the orbital Doppler shifts to first order in $e$; given the magnitudes of the uncertainties of our measurements, this should be an adequate approximation as long as $e \lesssim 0.2$.

We described the intrinsic spin frequency evolution with both $f$ and $\dot{f}$ terms:

$$f_{\text{spin}}(t) = f_0 + \dot{f}(t - t_0) + \ddot{f}(t - t_0)^2$$

(2)

![Figure 2](image1.png)

**Fig. 2.**—Representative photon spectra of 4U 1901+03 from the peak (February 16, or MJD 52,686) and late in the decay (June 28, MJD 52,818) of the 2003 outburst. The effect of the instrumental responses have been removed (“unfolded”). Data from PCU #2 are shown, along with data from HEXTE clusters 1 and 2. For the 2003 June 28 observation, we rebinned the HEXTE spectra by a factor of 4. Error bars indicate the 1$\sigma$ uncertainties. The top and bottom panels show the residuals to each model fit (units of normalized counts s$^{-1}$ keV$^{-1}$) for the 2003 February 16 and 2003 June 28 spectra, respectively.

![Figure 3](image2.png)

**Fig. 3.**—Pulse frequency of 4U 1901+03 throughout the 2003 outburst. The top panel shows the measured frequency for each observation (open squares) with error bars indicating the 1$\sigma$ uncertainties. The best-fit orbital model (Table 1) is plotted as a solid line; the model for the intrinsic spin evolution of the pulsar (excluding the orbital model) is plotted as a dashed line. The lower panel shows the residuals to the orbital model.
Pulse phase evolution with time: We fit the frequency model to the measurements using a nonlinear gradient-expansion algorithm (CURVEFIT in IDL). We achieved an acceptable fit ($\chi^2 = 77.22$ for 53 degrees of freedom) with orbital parameters $P_{\text{orb}} = 22.58$ d, $a \sin i = 106.9$ lt-sec and $e = 0.035$. We used this preliminary orbital model to perform a fit of the accumulated phase delay measurements. We first integrated equations (1) and (2) to obtain an expression for the pulse phase evolution with time:

$$\phi(t) = \phi_0 + f_0 (t - t_0) + \dot{f}(t - t_0)^2 + \ddot{f}(t - t_0)^3 - f_0 a_X \sin i (\sin l - \frac{a}{c} \cos 2l - \frac{b}{d} \sin 2l)$$

(3)

where $\phi_0$ and $t_0$ are the frequency and time, respectively, of the first frequency measurement and the $\dot{f}$, $\ddot{f}$ are constant over the outburst duration.

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(3)

where $\phi_0$ is an arbitrary reference phase, corresponding in this case to the peak of the fundamental of the first pulse observed in the first observation. We then fit this model to the measured pulse arrival times, defined as the peak of the fundamental Fourier component.

The frequency of observations during the first full orbital cycle of the outburst (between MJD 52,680 and 52,700) was such that we were able to unambiguously track the pulse phase over the entire cycle. Even so, we found significant residual phase delays which varied systematically on a timescale of a few days, with an rms amplitude of $\approx 0.1$ cycles. Although variations in the pulse profile over the entire outburst (see Fig. 5) may contribute to the residuals to the phase fit, residuals were also present during intervals when the pulse profile shape was relatively consistent. Thus, there is significant intrinsic timing noise present, perhaps arising from small changes in the instantaneous accretion rate.

Beyond MJD 52700 the 2–3 d gaps between the RXTE observations introduced the possibility of pulse count ambiguities, although only of magnitude $\pm 1$ cycle in general. We repeatedly computed the phase fit after adding or subtracting a cycle within the data gaps, in order to minimise the total $\chi^2$ until no further improvement was possible. Because of the timing noise, the resulting $\chi^2$ calculated using the errors on the individual phase measurements was much larger than the number of degrees of freedom. In order to estimate the confidence limits for the orbital parameters, we re-scaled the pulse arrival time errors so that the resulting $\chi^2$ was 1 per degree of freedom. We then varied each parameter in turn, fitting with all other parameters free to vary, to determine the parameter range for which the rescaled $\chi^2 \leq \chi^2_{\text{min}}(1 + 1/n)$, where $n$ is the number of degrees of freedom (1473 for the full set of arrival time measurements). The resulting orbital parameters and uncertainties are listed in Table I. The predicted frequency, intrinsic spin frequency for the neutron star and the residuals from the model are shown in Fig. 3. The pulse arrival time delays with respect to the intrinsic spin evolution model are shown in Fig. 4.

Our best-fit parameters describing the intrinsic spin evolution indicate that the spin-up rate was initially around $3 \times 10^{-11}$ Hz s$^{-1}$, similar to the maximum measured for other transient pulsars (e.g. Bildsten et al. 1997). According to the intrinsic spin model, the spin-up decreased throughout the outburst, falling to zero just before the end of the outburst, around MJD 52,824. The
2.5–25 keV flux by this time had dropped to around $5.5 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$.

### 3.3. Pulse profile variability

The pulse profile was consistently non-sinusoidal, and exhibited several intervals of stability punctuated by relatively rapid change. The fractional pulse amplitude also varied over the outburst, and was generally between 4 and 22% (rms). From the beginning of the outburst until 2003 March 3 the profile was consistently similar to the example shown from February 19 (MJD 52,689; Fig. 5). During that observation the pulse amplitude was 15% rms. Between March 3 and 13 the profile switched to the characteristic double-peaked shape of March 19; also on March 13 the rms amplitude dropped to 7%. The profile continued to evolve throughout March and April, with gradually increasing pulse fraction and small drifts of the harmonic components until another abrupt shift between 2003 June 14–18. The pulse amplitude had risen to 13% rms on June 14 before falling abruptly to 9% rms on June 18, and then recovering to an overall maximum for the outburst of 22% rms on June 28. After this final peak, the profile remained similar in shape but with steadily decreasing amplitude towards the end of the outburst. Pulsations became undetectable (< 1% rms) after 2003 July 13 (MJD 52,833), by which time the 2.5–25 keV flux had dropped to below $3 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$.

### 3.4. A search for the optical/IR counterpart

Following the improved X-ray position obtained from the PCA scan (Galloway et al. 2003a), we examined the field of 4U 1901+03 in Digital Sky Survey and 2MASS images to identify the optical counterpart. The mass function implies a minimum companion mass (assuming a 1.4$M_\odot$ neutron star) of 4.5$M_\odot$. The most probable companion mass (for an inclination of 60°) is 6.0 $M_\odot$. The donor stars in long-period binary pulsars are typically either Be stars or (sometimes Roche-lobe filling) OB supergiants. The column density interpolated from Hi survey observations towards the source is between (1.1–1.24) x 10$^{22}$ cm$^{-2}$ (Dickey & Lockman 1990; Stark et al. 1992), which translates to an $A_V = 6.1$–6.9 (assuming a standard dust to gas ratio; Predehl & Schmitt 1995). Alternatively, the reddening estimated from dust IR emission is higher at $A_V = 10.2$ (Schlegel et al. 1998).

The USNO A2.0 astrometric catalog (Monet et al. 1998) contains just two stars within the 1' error circle of 4U 1901+03 having colors consistent with early-type stars suffering extinction with $A_V > 6$ (i.e. $B - R > 3$; Fig. 6, upper panel). We obtained low-resolution spectra of these two candidates using the Low Dispersion Survey spectrograph (LDSS-2) on the 6.5 m Clay (Magellan II) telescope at Las Campanas, Chile. We accumulated two 600 s spectra of each candidate on 2003 August 10, using the medium red grism with a 1' long slit, covering the range 4500–9000 Å. However, the overall spectral features suggest that these candidates are instead low-mass K0–5 stars (Fig. 6, lower panel), which are ruled out as the counterpart on the basis of the X-ray mass function. Clearly, it is not possible to distinguish between early-type stars with high extinction and nearby late-type stars from optical photometry alone.

Thus, we also examined the $J$, $H$ and $K$ magnitudes of candidates within 1' of the X-ray position from the 2MASS point source catalogue. The expected range of colors for a B-star for the estimated extinction range are $J - H = 0.5$–1.1 and $H - K = 0.3$–0.6 (Cox 2000). The colors expected for a supergiant counterpart fall within similar ranges, slightly larger in $J - H$ and smaller in $H - K$. We found approximately ten stars in the 1' RXTE error circle with colors within these ranges, including the optically identified candidates A and B. Star B was the brightest in the IR bands, with $J = 11.5$; this is the only star consistent with the expected brightness of a supergiant counterpart at $d \lesssim 10$ kpc, and can be ruled out as the counterpart on the basis of our spectroscopic observations. Two other stars had $J$ magnitudes similar to that of star A, at $J \approx 13$; we expect these candidates are also nearby low-mass stars, like star A. The remaining candidates all had $J > 14$, much fainter than the limit of $J \approx 12$ expected for a supergiant companion at $d \lesssim 10$ kpc. Several of these stars were not detected in the DSS image, suggesting that $B \gtrsim 20$ perhaps consistent with the upper end of the estimated $A_V$ range towards the source.

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Fig. 6.— Upper panel Field of 4U 1901+03 from the DSS POSS-II data, showing the 1' RXTE error circle and the two candidate counterparts A and B identified by their large $B - R$ color indices. The $B$-magnitudes measured from the USNO-A2.0 catalog, are 18.5 and 19.3, respectively; star B is also the brightest star within the 1' error circle in IR at $J = 11.5$. Lower panel Magellian spectra of the candidates A and B, as well as a comparison spectrum from a K2V star, HD 22079 (Danks & Dennefeld 1992). The spectra of A and B were dereddened with $E(B - V) = 1.1$ and 1.5 respectively (Fitzpatrick 1999). The spectra of stars A and B are consistent with K0–5 stars and thus can both be ruled out as the counterpart of 4U 1901+03.
4. DISCUSSION

4U 1901+03 is one of a small, but growing class of low-eccentricity high-mass X-ray binaries. Although we were unable to identify the optical counterpart, the limit of $J \gtrsim 13$ for stars in the $1'$ RXTE error circle rules out a supergiant companion, unless the distance to the source is $> 10$ kpc.

Furthermore, the source is located on the Corbet diagram (Corbet 1986) with confirmed Be transients such as 4U 0115+63 (e.g. Bildsten et al. 1997). Like that source, 4U 1901+03 exhibits infrequent outbursts that can span multiple orbital periods, a behavior quite unlike the typically persistent activity of partially Roche-lobe filling supergiants. If the mass donor is not filling its Roche lobe, the efficacy of tidal forces in circularizing such a wide orbit is negligible, which makes the present low eccentricity of 0.036 difficult to understand (given the initially eccentric orbit expected to arise as a result of the natal supernova kick). As suggested by Pfeil et al. (2002), the formation events for low-eccentricity O-B transients like 4U 1901+03 may be dynamically distinct from the more common high-eccentricity binaries due to a much lower initial kick to the neutron star.

The lack of eclipses indicates the inclination is $\lesssim 85^\circ$. The 95% upper limit on the companion mass for an a priori isotropic distribution of inclination angles is $88 \ M_\odot$. The estimated peak bolometric luminosity (for a distance of 10 kpc) was $1.1 \times 10^{38}$ ergs s$^{-1}$, and the integrated luminosity over the course of the outburst was $7.4 \times 10^{34} (d/10\text{ kpc})^2$ ergs (for a neutron star with $R = 10$ km and $M = 1.4 \ M_\odot$). The maximum intensity observed by Uhuru during the 1970–1 outburst was $87 \pm 11$ count s$^{-1}$ at epoch 1971.0, corresponding to $1.5 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ in the range 2–6 keV (Forman et al. 1972). Our broadband RXTE spectra suggest that 20–30% of the source flux is emitted in this energy range, so that the estimated maximum bolometric luminosity for the Uhuru observations was $\approx 8 \times 10^{37}$ ergs s$^{-1}$ (for $d = 10$ kpc), consistent with the peak RXTE value to within the error. Vela 5B measured a peak of $\approx 8$ count s$^{-1}$ around epoch 1970.9 (Priedhorsky & Terrell 1984). The maximum observed flux was thus $3.6 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$ in the range 3–12 keV, in which range 60% of the flux observed by RXTE is emitted; thus, the estimated maximum bolometric luminosity measured by Vela 5B was $7 \times 10^{37}$ ergs cm$^{-2}$ s$^{-1}$, roughly consistent with both the Uhuru measurements of the 1970–1 outburst and the the peak measured by RXTE for the 2003 outburst. We also note that the estimated duration of the 1970–1 outburst (excluding the peak around epoch 1970.6) was at least 120 d, similar to the 150 d duration of the 2003 outburst. No emission prior to 2003 February was detected by the RXTE/ASM, although there is the possibility that one or more intervening outbursts occurred sometime between 1971 and the launch of RXTE in 1995. A similarly bright outburst before 1980 would probably have been detected by Vela 5B or the ASM onboard Ariel 5 (Hol 1976). An outburst between 1987 and 1996 would likely have been detected with the Ginga ASM (operational until 1991 November; Tsunemi et al. 1985) or the BATSE experiment onboard CGRO (1991 April to 2000 June, Zhang et al. 1995). Assuming no intermediate outbursts occurred, we derive a time-averaged accretion rate for a 32.2 yr recurrence time of $8.1 \times 10^{-11} (d/10\text{ kpc})^2 M_\odot\text{ yr}^{-1}$. We note that the 32.2 yr interval between outbursts in 4U 1901+03 may be the longest presently known for any X-ray transient.

Whilst no cyclotron absorption features were detected in the X-ray spectrum, the observed range of source flux over which pulsations were detected allows a rough estimate of the dipole magnetic field strength of the neutron star. Assuming that a disk is present, it must be truncated above the surface of the neutron star in order to allow the magnetic field to channel the accreting material and produce observable pulsations. The truncation radius $r_M$ is inversely proportional to the mass accretion rate (e.g. Frank et al. 1992), so that the requirement for $r_M > R_\star$ (where $R_\star \approx 10$ km is the neutron star radius) even at the peak of the outburst implies a lower limit on the magnetic field strength (although for 4U 1901+03 this limit is several orders of magnitude below the canonical field strength for long-period pulsars of $\sim 10^{12}$ G). For accretion to be dynamically feasible also requires that the inner disk radius is within the corotation radius $r_{\text{co}}$, i.e. the radius at which the Keplerian orbital frequency equals the neutron star spin frequency. For the lowest flux at which pulsations were detected, this implies that $B < 0.5 \times 10^{12} (d/10\text{ kpc})^2$ G, giving a fundamental cyclotron frequency of $\nu_{\text{cycl}} \lesssim 4 (d/10\text{ kpc})^2$ keV. This is consistent with the absence of detectable cyclotron features in the broadband spectrum, although it is possible that the residuals frequently present at $\lesssim 10$ keV may arise from higher harmonics of a low-energy cyclotron absorption line. We can also estimate the magnetic moment by assuming that the long-term mass accretion has left the pulsar close to spin equilibrium, i.e. $r_M \approx r_{\text{co}}$ (e.g. Bildsten et al. 1997). In that case, we find $B \approx 0.3 \times 10^{12} (d/10\text{ kpc})^{-6/7}$ G, consistent with the above estimate. We note that the inferred limit on $\nu_{\text{cycl}}$ and the low values of $kT_\nu$ are qualitatively consistent with the observed correlation in other pulsars between the cyclotron energy and the spectral cutoff (e.g. Coburn et al. 2002).

Identification of the counterpart to 4U 1901+03 is essential to confirm the nature of the mass donor suggested by these observations, which may prove difficult unless the source becomes active again. If the outbursts occur regularly every $\approx 30$ yr, significantly more advanced X-ray instruments may be available for the next outburst, perhaps sufficient to measure the position more precisely and identify the optical counterpart, as well as resolve the residuals below 10 keV and measure the properties of the low-energy cyclotron lines, thus allowing direct measurement of the field strength.

This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation. 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 was supported in part by the NASA Long Term Space Astrophysics program under grant NAG 5-9184.

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