HIGH-RESOLUTION X-RAY SPECTROSCOPY OF THE ULTRACOMPACT LMXB PULSAR 4U 1626−67

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ABSTRACT

We report results from four recent observations of the ultracompact LMXB pulsar 4U 1626−67. These observations obtained high-resolution X-ray spectra with Chandra HETGS and XMM RGS, allowing us to study in detail the prominent Ne and O emission-line complexes. The observations were spaced over a period of 3 yr, enabling us to monitor the line regions as well as the overall spectral and timing properties. The structure of the emission lines and the helium-like Ne IX and O VIII triplets support the hypothesis that they are formed in the high-density environment of an accretion disk. We do not find any significant variability in the line widths or ratios, though we note that the equivalent widths decrease. Using the most recent calibration products, we are able to place constraints on the strengths of the Ne K, Fe L, and O K photoelectric absorption edges. In contrast to our earlier analysis, the data do not require an overabundance of Ne or O in the system relative to the expected ISM values. We find that the pulsar is still spinning down but note that the pulse profile has changed significantly from what was found prior to the torque reversal in 1990, suggesting a change in the geometry of the accretion column. The flux of 4U 1626−67 continues to decrease, following the trend of the last 30 yr over which it has been observed. Taking into consideration current theory on disk stability, we expect that 4U 1626−67 will enter a period of quiescence in 2−15 yr.

Subject headings: binaries: close — pulsars: individual (4U 1626−67) — stars: neutron — X-rays: binaries

1. INTRODUCTION

The 7.7 s X-ray pulsar 4U 1626−67 was first discovered by Uhuru (Giacconi et al. 1972; Rappaport et al. 1977) and remains the only known high-field (B ∼ 4 × 1012 G, Pravdo et al. 1979; Coburn et al. 2002) pulsar in an ultracompact low-mass X-ray binary (LMXB). This unique pairing of an apparently young neutron star with a very low mass companion could indicate that the neutron star was originally a white dwarf whose mass, as a result of accretion, exceeded the Chandrasekhar limit (Joss et al. 1978; although see Verbunt et al. 1990). Although orbital motion has never been detected in X-ray data, pulsed optical emission reprocessed on the surface of the secondary allowed Middleditch et al. (1981) to infer an orbital period of 42 minutes, which was later confirmed by Chakrabarty (1998). It is therefore a member of the class of objects known as “ultracompact” binaries (Porb < 80 minutes), which must have hydrogen-depleted secondaries to reach such short periods (Paczynski & Sienkiewicz 1981; Nelson et al. 1986). It has an extremely small mass function of f < 1.3 × 10−6 M⊙, which corresponds to a secondary mass of 0.04 M⊙ for i = 18° (Levine et al. 1988). A very low mass secondary would account for the faint (V ∼ 17.5) optical counterpart and the high optical pulsed fraction (McClintock et al. 1977, 1980).

Initially, 4U 1626−67 was observed to be spinning up with a characteristic timescale Ω/Ω ≈ 5000 yr, but in 1990 this trend reversed and the neutron star began to spin down on approximately the same timescale (Wilson et al. 1993; Chakrabarty et al. 1997). The torque reversal was abrupt, although the decrease in bolometric X-ray flux has been gradual and continuous over the past 30 yr. Assuming that the X-ray flux is a good proxy for the accretion rate onto the neutron star, these observational facts cannot be reconciled with current accretion disk–neutron star interaction theory. However, the fact that the pulsar underwent torque reversal implies that the radius at which the accretion disk is truncated by the neutron star’s magnetic field is close to the corotation radius. With this assumption and a neutron star mass of 1.4 M⊙, the measured P during spin-up can constrain the accretion rate to be ≥ 2 × 10−10 M⊙ yr−1, which implies a distance of ≥ 3 kpc (Chakrabarty et al. 1997). Alternatively, measurements of the optical and X-ray fluxes (assuming the albedo of the disk is ≥ 0.9) give a distance range to 4U 1626−67 of 5 ≤ D ≤ 13 kpc (Chakrabarty 1998).

Perhaps the most unique characteristic of 4U 1626−67 is its X-ray spectrum. Angelini et al. (1995) first reported the presence of Ne and O emission lines in an ASCA (Advanced Satellite for Cosmology and Astrophysics) spectrum, and they found similar features in an Einstein observation performed prior to the torque reversal. Using a subsequent observation by Chandra, we discovered double-peaked line structure indicative of formation in an accretion disk (Schulz et al. 2001, hereafter S01). Emission-line features such as these are not seen in any other LMXB systems and suggest that the donor is particularly rich in elements resulting from later stages of nuclear burning—perhaps a C-O-Ne or O-Ne-Mg white dwarf. A UV spectrum

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obtained with the Hubble Space Telescope Space Telescope Imaging Spectrograph (STIS) revealed both emission and absorption features from C, O, and Si (Homer et al. 2002). The C absorption lines are stronger than expected from a purely interstellar medium (ISM) contribution, suggesting some local contribution, and the O v line has a pronounced double-peaked profile, indicating an accretion-disc origin similar to the X-ray lines. The spectrum is missing common N and He lines typically seen in UV spectra from high-excitation systems, likely because 4U 1626–67 is lacking in these elements. A high-S/N optical spectrum obtained by Werner et al. (2006) using the Very Large Telescope confirms the lack of He in the system and finds H lacking as well. The optical spectrum is dominated by C and O emission lines, but does not appear to contain any Ne lines.

We present a series of four high-resolution X-ray spectra spanning three years, two obtained with the High Energy Transmission Gratings (HETGs) aboard the Chandra X-Ray Observatory, and two from the Reflection Grating Spectrometers (RGSs) aboard XMM-Newton. We previously presented analysis of the first Chandra observation in S01, but this reanalysis uses improved calibration products and software. We describe the observations and data reduction procedures in § 2, and our spectral analysis in § 3. We present timing analysis in § 4. Finally, we discuss the implications of our observations in § 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Chandra

The pulsar 4U 1626–67 has been observed twice with the HETGS on board the Chandra X-Ray Observatory (Canizares et al. 2005), first on 2000 September 16 and again on 2003 June 3. The HETGS comprises two sets of transmission gratings: the medium energy gratings (MEGs), with a spectral resolution of $\Delta \lambda = 0.023 \, \text{Å FWHM}$ and a range of 2.5–31 Å (0.4–5.0 keV), and the high energy gratings (HEGs), which have $\Delta \lambda = 0.012 \, \text{Å FWHM}$ and a range of 1.2–15 Å (0.8–10 keV). See Table 1 for a summary of the observations.

We obtained “level 1” event lists from the Chandra data archive\(^2\) and reprocessed the data using the latest available version of the CIAO software (vers. 3.3) and the calibration database (CALDB vers. 3.2.1). This processing applied the gain, time-dependent gain, and charge transfer inefficiency (CTI) corrections. The CTI corrections improve the computation of event grade (used to filter out likely nonsource events) and the gain products improve the channel to energy mapping of events, which allows for more precise order-sorting of the dispersed spectra. We created grating responses that include the time-dependent effects of a contaminant present on the ACIS optical blocking filter (Marshall et al. 2004). Correcting for this contamination is necessary for precise spectral analysis, since it affects both spectral shape and normalization.

Neither Chandra observation contained any appreciable background flares. After reprocessing and filtering out bad pixels, we applied the standard grade filtering (retaining grades 0, 2, 3, 4, and 6) and used the tgdetect tool to determine the zeroth-order source position. The high source count rate caused the zeroth-order images to be quite piled up, but this did not hinder our ability to determine the source position. This position was used to sort the dispersed spectra into the proper orders, resulting in 62,555 (101,799) background-subtracted events in the first-order MEG spectrum and 35343 (59706) in the first-order HEG spectrum for ObsID 104 (3504). The dispersed spectra are not affected by pileup.

2.2. XMM-Newton

XMM-Newton has observed 4U 1626–67 four times, but only two of these observations contain a significant amount of science data (ObsIDs 0111070201, performed 2001 August 24, and 0152620101, performed 2003 August 20; see Table 1). Here we analyze data from the three EPIC cameras (two MOS detectors and the PN), as well as the two reflection grating spectrometers (RGS1 and RGS2). The MOS (pn) detectors have nominal bandpasses of 0.15–12 (0.15–15) keV and spectral resolutions of 70 (80) eV at 1 keV. The RGSs have bandpasses of 0.35–2.5 keV and first-order spectral resolutions of 0.04 Å FWHM. Both observations were performed after the failure of RGS1’s CCD7 and RGS2’s CCD4, resulting in gaps in the dispersed spectra that were filtered out for analysis.

The XMM-Newton science products were obtained from the HEASARC archive.\(^3\) Both observations were affected by high background flares in the MOS and pn detectors, which we filtered out prior to analysis, resulting in the loss of $\approx 5$ ks of MOS data and $\approx 2$ ks of pn data for ObsID 0111070201, and $\approx 25$ ks of MOS and pn data and $\approx 12$ ks of RGS data for ObsID 0152620101.

During ObsID 0111070201, the MOS1 detector was in timing mode, so was not easily susceptible to pileup. However, the source core is somewhat piled in the MOS2 detector, and was excised prior to analysis. During ObsID 0152620101, the MOS2 detector was in timing mode, and the MOS1 detector shows mild evidence of pileup, so we again removed the central portion of source data prior to analysis. The standard filters were applied, FLAG $= 0$ and PATTERN $< 12$ (4), to the MOS (pn) data. The RGS data were reprocessed (using XMMASAS vers. 6.5.0) with refined source coordinates, resulting in updated source and background spectra as well as responses. Background spectra were created for the EPIC data using off-source regions, and scaled appropriately to match the source spectra. After processing, there were a total of $1.1 \times 10^5$ (1.7 $\times 10^5$) background-subtracted counts in the MOS1 data, 7.3 $\times 10^4$ (4.5 $\times 10^5$) in the MOS2 data, 3.1 $\times 10^5$ (1.04 $\times 10^5$) in the pn data, 8366 (17289) in the RGS1 spectrum, and 9951 (21076) in the RGS2 spectrum for ObsID 0111070201 (0152620101).

3. SPECTRAL ANALYSIS

We used the ISIS software package (vers. 1.3.3)\(^4\) for spectral fitting. All source and background data, as well as response files, were read into ISIS, and normalized background counts were subtracted prior to fitting. We combined the $\pm 1$ spectral orders of the HETGS data, and used the –1 order of the RGS data. We employed Cash statistics throughout our analysis, and fit the data

| Observatory     | Observation Start (UT) | Observation ID | Duration (ks) |
|-----------------|------------------------|----------------|--------------|
| Chandra          | 2000 Sep 16 14:57      | 104            | 40           |
| XMM-Newton       | 2001 Aug 24 02:57      | 0111070201     | 17           |
| Chandra          | 2003 Jun 3 02:30       | 3504           | 97           |
| XMM-Newton       | 2003 Aug 20 05:55      | 0152620101     | 84           |

\(^2\) At http://cda.harvard.edu/chaser/mainEntry.do.

\(^3\) At http://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl.

\(^4\) See http://space.mit.edu/CXC/ISIS.
from different instruments simultaneously. All the quoted errors are 90% confidence limits unless otherwise noted.

3.1. Continuum Fitting

For continuum fitting, we excluded the known emission-line regions and used the wavelength/energy ranges 1.2–17.0 (1.8–26.0) Å for the HEG (MEG) grating spectra, 7.0–34.0 Å for the RGS grating spectra, and 1.1–9.9 (1.1–8.3) keV for the MOS (pn) spectra. The lower energy ranges of the MOS and pn spectra were excluded because they contain unresolved Ne and O emission lines which artificially increase the overall continuum level. We also excluded regions in the RGS data that contain bad columns or fall across nonfunctioning CCD chips. During the second XMM-Newton observation (ObsID 0152620101), MOS2 was in timing mode, and its spectral calibration did not match that of the other instruments, so these data were omitted from the continuum fit.

We grouped the MOS data to have a minimum of 50 counts and the PN data to have a minimum of 500 counts bin$^{-1}$ and the RGS data to contain 6 channels bin$^{-1}$ (resulting in $0.04 \times 0.08$ wavelength bins, comparable to the instrumental resolution). We grouped the HEG and MEG spectra to contain 4 channels and a minimum of 10 counts bin$^{-1}$ (resulting in $0.01 \times 0.02$ wavelength bins for the HEG [MEG] data, again comparable to the instrumental resolution).

Although a simple power-law model gives a reasonable fit ($\chi^2_{\nu} \simeq 1.2$), the residuals suggest the presence of an additional spectral component. This has previously been modeled as a second power-law or a blackbody component (S01). An $F$-test indicates that the addition of a blackbody component is preferred

![Graph](image1.png)

**Fig. 1.**—Combined Chandra (top) and XMM-Newton (bottom) spectra with representative continuum models comprised of absorbed blackbody plus power-law emission. The blackbody (dot-dashed line) and power-law (dashed line) contributions are also plotted.

![Graph](image2.png)

**Fig. 2.**—X-ray flux history of 4U 1626–67 from 1977 to 2003. The dashed line is a linear fit, the dot-dashed line a logarithmic fit to the data. Error bars represent the 1σ confidence intervals. The most recent four data points represent the Chandra and XMM-Newton observations.

| Observation          | $N_{HI}$ $(10^{21} \text{cm}^{-2})$ | Norm.$^a$ | $\Gamma$ | $R_{10kpc}^2/D_0^2$ | $kT$  | Flux$^b$ | $C_r$ (dof)$^c$ |
|----------------------|-----------------------------------|-----------|---------|---------------------|------|---------|----------------|
| Chandra ObsID 104    | $1.3^{+0.4}_{-0.3}$               | 12.1 ± 0.5 | 0.88 ± 0.03 | 600.4–680.2         | 0.21 ± 0.02 | 2.2 | 1.04 (1844) |
| XMM-Newton ObsID 0111070201 | $1.39^{+0.07}_{-0.09}$           | 8.0 ± 0.2  | 0.80 ± 0.01 | 330.3–390.0         | 0.254 ± 0.008 | 1.7 | 1.15 (1888) |
| Chandra ObsID 3504   | $1.0^{+0.3}_{-0.3}$               | 8.4 ± 0.2  | 0.81 ± 0.02 | 600.4–680.2         | 0.19 ± 0.01 | 1.7 | 1.10 (1926) |
| XMM-Newton ObsID 0152620101 | $1.38^{+0.06}_{-0.04}$           | 6.76 ± 0.05 | 0.782 ± 0.009 | 290.8–380.0         | 0.245 ± 0.005 | 1.5 | 1.36 (1857) |

$^a$ Normalization of power-law component at 1 keV in units of $10^{-3}$ ergs cm$^{-2}$ s$^{-1}$ keV$^{-1}$.

$^b$ Absorbed 0.3–10.0 keV flux in units of $10^{-10}$ ergs cm$^{-2}$ s$^{-1}$.

$^c$ The reduced Cash statistic and number of degrees of freedom for the fit.
over a single power-law at the 8 $\sigma$ level, and this is what we use for our continuum fits. To model the absorption, we used an updated version of the tbabs model, tbnew\(^5\) (J. Wilms et al. 2007, in preparation), which includes high-resolution structure for the Ne K, Fe L, and O K edges. The best-fit continuum models are presented in Table 2, and the combined continuum spectra are shown in Figure 1.

The 0.3–10 keV flux followed a decreasing trend, falling from $2.2 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ in 2000 September to $1.5 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ in 2003 August. Overall, 4U 1626–67 has decreased in flux since 1977, with no apparent change following the reversal in accretion torque in 1990 (see Fig. 2).

3.2. Emission Lines

There are prominent Ne and O emission lines in all four spectra (see Figs. 1 and 3). To explore the line characteristics, we added Gaussian features to the continuum models determined from the overall spectral fits. All the lines are well fit by single Gaussian profiles. We note that the Ne $\alpha$ lines are not reliably detected in the XMM-Newton data; for these lines, we fixed the

\(^5\) See http://astro.uni-tuebingen.de/~wilms/research/tbabs.
line width and location to the Chandra values to obtain approximations of the line flux. The single-Gaussian line fits are presented in Table 3.

The single-Gaussian fits reveal lines which are quite broad (≈6000 km s\(^{-1}\) FWHM). For a given line, the width does not vary significantly over the four observations. However, the line strengths of Ne \(x\) and O \(vii\) decrease over the course of the observations (the trend is not so clear for Ne \(ix\) or O \(vii\)). To determine whether the line flux is decreasing more rapidly than the overall continuum flux, we fixed the line widths to their weighted averages and recalculated the line strengths, then fit the line flux trends for the Ne \(x\) and O \(vii\) lines. Fixing the widths did not change the flux values appreciably and improved the errors on the fluxes by only a small amount. Over the ≈3 yr span of the observations, from 2000 September to 2003 August, the Ne \(x\) flux decreased to 51.6% ± 5.5% and the O \(vii\) flux to 54.0% ± 8.7% of their initial values. This decrease is significantly more than the decrease in the 0.3–10.0 keV continuum flux, which only fell to 76.4% ± 6.6% of its initial value. The fact that the line strengths decrease faster than the continuum strength is also reflected in the declining equivalent widths (EWs) of the lines. We find that the EWs of Ne \(x\) and O \(vii\) decrease to 75.7% ± 7.9% and 74.3% ± 12.3% of their initial values, respectively (see Fig. 4, which also includes data from ASCA and BeppoSAX).

The Chandra Ne \(x\) and O \(vii\) lines, as well as the XMM-Newton O \(vii\) line, show what appear to be double-peaked profiles (see Fig. 3). As S01 point out, the line shapes, combined with the apparent high-density environment of the line formation regions (as indicated by the dominance of the intercombination component of the He-like triplets; see below), suggest that the lines arise in an accretion disk. To derive physically meaningful values for the line parameters, we fit each line with a pair of Gaussians, fixing the width and absolute velocity of the red- and blueshifted components to be equal, thus approximating the expected disk-line "two-horn" profile. However, there are a number of instances in which it is not possible to constrain the widths and velocities of a given line. For these instances, we fixed the values to the weighted averages from the observations for which the line was well constrained. This allowed us to evaluate the approximate fluxes of the line components, with the assumption that the widths and velocities of a given line do not change substantially over the course of the observations. Where multiple measurements could be made, this is true both for the widths from the single-Gaussian fits and for the widths and velocities from the double-Gaussian fits, so we consider it to be a reasonable assumption. The Ne \(ix\) lines in the XMM-Newton data were too poorly constrained to be included in the double-Gaussian fits. Table 4 contains the values obtained from these fits.

Fitting the helium-like triplets of Ne \(ix\) and O \(vii\) with multiple Gaussians allowed us to estimate the strengths of the resonance, intercombination, and forbidden lines. The Ne \(ix\) intercombination line is clearly dominant in both Chandra observations (we were unable to fit this line in the XMM-Newton observations). While the intercombination line is the strongest of the O \(vii\) triplet as well, the resonance line contains significant flux, whereas the forbidden lines do not contribute substantially to any of the triplets. The lack of forbidden lines suggests that we may be observing emission from a high-density plasma, which would support the hypothesis that the lines arise in the accretion disk. We discuss this further in § 5.2.

### Table 3

| Instrument | MJD | \(\Delta \lambda\) (Å) | \(V\) (km s\(^{-1}\)) | FWHM (km s\(^{-1}\)) | Flux (Å eV\(^{-1}\)) | EW (Å eV\(^{-1}\)) |
|------------|-----|----------------------|-----------------------|-----------------------|-------------------|-----------------|
| Chandra    | 51,803.6 | 0.021 ± 0.014 | 510 ± 340 | 6390±280 | 41.3±4.6 | 0.29 [24] | 0.97 (115) |
| XMM-Newton | 52,145.1 | 0.016 ± 0.015 | 390±305 | 4800±1600 | 25.0±3.2 | 0.21 [17] | 1.22 (16) |
| Chandra    | 52,795.1 | 0.018 ± 0.013 | 440±320 | 5540±590 | 19.4±2.1 | 0.20 [17] | 1.04 (134) |
| XMM-Newton | 52,871.2 | 0.019 ± 0.021 | 470±320 | 5540±990 | 20.4±3.5 | 0.21 [18] | 2.15 (16) |

The single-Gaussian emission-line fits

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\(a\) The Gaussian normalization in units of 10\(^{-5}\) photons cm\(^{-2}\) s\(^{-1}\).

\(b\) The reduced Cash statistic and number of degrees of freedom for the fit.

\(c\) Since the XMM-Newton data were not able to constrain the Ne \(ix\) lines, their positions and widths were fixed to the values found in the Chandra data.
require a statistically significant local contribution to the interstellar column depth (see § 5.1 for further discussion).

4. TIMING ANALYSIS

All of the Chandra and XMM-Newton observations of 4U 1626−67 have high enough time resolution to determine the pulse period, and the XMM-Newton observations also allowed us to create energy-resolved pulse profiles. Prior to performing the timing analysis, we corrected the photon arrival times to the location of the solar system barycenter.

To determine the pulse period, we computed an overresolved power spectrum using the technique described in Chakrabarty (1998). We calculated the pulse frequency and frequency error using the methods and formulae presented in Ransom et al. (2002). The results are shown in Table 6, and Fig. 5 contains a plot of the frequencies as well as the prediction curve and associated errors extrapolated from previous Compton Gamma Ray Observatory BATSE monitoring results (Chakrabarty et al. 1997). As can be seen from the plot, the pulsar is spinning down faster than was predicted, which is significant with respect to the stability of the timing during the BATSE era but not unexpected considering the variable spin history of the source. We note that the QPO at 0.048 Hz is present in each of the observations, as has been seen previously (Shinoda et al. 1990; Chakrabarty 1998).

The XMM-Newton pn data are ideal for creating energy-resolved pulse profiles. We made four energy cuts and divided the pulse period into 40 bins to create the profiles presented in Figures 6 and 7. The profiles have some significant differences from what was seen previously (see, e.g., Pravdo et al. 1979; Kii et al. 1986; McClintock et al. 1980; Levine et al. 1988). In the earlier observations, the pulse profile shows a dip at energies ≤2 keV, then the emergence of two prominent peaks that flank this dip as the energy increases, reaching a maximum at ≈5 keV. By ≈13 keV, the dip has returned, and it becomes both broader and deeper as the energy increases. We find that the current pulse profiles lack the double-peak feature that was seen before, and show only a dip which broadens at lower and higher energies. The profile is not entirely symmetric; there also appears to be a secondary dip at phase ≈0.85. Insofar as the pulse profile reflects the geometric and radiative properties of the accretion column and neutron star hot spot (see, e.g., Kii et al. 1986), changes in the pulse profile suggest that there have been fundamental changes in these regions of the system. While we do not speculate here as to the exact nature of these changes, we note that the accretion geometry may have changed at the time of torque reversal, affecting the accretion flow at the neutron star surface. Therefore, the changes that are seen in the pulse profile may be related to the change in the continuum spectrum of 4U 1626−67 that was observed around the time of the torque reversal (Angelini et al. 1995).

We also note that there were no flaring events seen in any of our observations, in contrast to what has been previously observed, when 4U 1626−67 was seen to flare dramatically in both X-ray and optical data on timescales of ≈1000 s (Joss et al. 1978; McClintock et al. 1980; Li et al. 1980). The cessation of flaring activity may have occurred at the same time as the torque reversal, although it is not clear what physical mechanism was responsible for the flaring or why it would be correlated with the change in sign of $\dot{P}$ (Chakrabarty et al. 2001).

5. DISCUSSION

5.1. Absorption-Edge Measurements

Four known or candidate ultracompact binary systems have X-ray spectra that show evidence of high Ne/O ratios.
### Table 4: Double-Gaussian Emission-Line Fits

| OBSERVATORY |
|-------------|
| Chandra | 51,803.6 | 3690 ± 1100 |
| XMM-Newton | 52,145.1 | 1500 ± 1500 |
| Chandra | 52,795.1 | 3040 ± 700 |
| XMM-Newton | 52,871.2 | 3085 |

| FWHM (km s⁻¹) | Δλ (Å) | V (km s⁻¹) | BLUEhifted Lines | REDshifted Lines |
|---------------|--------|------------|-----------------|-----------------|
| **Ne x Line at 12.13 Å** |
| Chandra | 51,803.6 | ±0.075 ± 0.011 | ±1840 ± 270 | 15.8 ± 3.1 | 0.104 [8.94] | 23.8 ± 3.8 | 0.160 [13.36] | 1.02 (246) |
| XMM-Newton | 52,145.1 | ±0.077 ± 0.012 | ±1910 ± 350 | 11.1 ± 2.3 | 0.092 [7.82] | 14.4 ± 3.3 | 0.120 [9.99] | 1.15 (33) |
| Chandra | 52,795.1 | ±0.068 ± 0.007 | ±1670 ± 130 | 8.2 ± 1.5 | 0.083 [7.05] | 10.5 ± 1.6 | 0.107 [8.94] | 1.10 (281) |
| XMM-Newton | 52,871.2 | ±0.072 ± 0.017 | ±1780 ± 420 | 11.3 ± 2.6 | 0.113 [9.45] | 9.0 ± 2.3 | 0.089 [7.60] | 1.86 (34) |

| **Ne xi Resonance Line at 13.45 Å** |
| Chandra | 51,803.6 | 1300 ± 0.055 | ±1210 | 0.117 ± 0.01 | 0.001 [0.05] | 0.117 ± 0.01 | 0.001 [0.05] | 1.09 (113) |
| Chandra | 52,795.1 | 1300 ± 0.055 ± 0.017 | ±1210 ± 130 | 11.1 ± 0.0 | 0.012 [0.80] | 11.1 ± 0.0 | 0.012 [0.80] | 0.86 (120) |

| **Ne xi Intercombination Line at 13.55 Å** |
| Chandra | 51,803.6 | 1300 ± 0.055 | ±1210 | 0.217 ± 0.02 | 0.001 [0.09] | 0.217 ± 0.02 | 0.001 [0.09] | 1.09 (113) |
| Chandra | 52,795.1 | 1300 ± 0.055 ± 0.017 | ±1210 ± 130 | 11.0 ± 0.0 | 0.012 [0.80] | 11.0 ± 0.0 | 0.012 [0.80] | 0.86 (120) |

| **Ne xii Forbidden Line at 13.70 Å** |
| Chandra | 51,803.6 | 1300 ± 0.055 | ±1210 | 0.217 ± 0.02 | 0.001 [0.09] | 0.217 ± 0.02 | 0.001 [0.09] | 1.09 (113) |
| Chandra | 52,795.1 | 1300 ± 0.055 ± 0.017 | ±1210 ± 130 | 11.0 ± 0.0 | 0.012 [0.80] | 11.0 ± 0.0 | 0.012 [0.80] | 0.86 (120) |

| **O vi Resonance Line at 21.60 Å** |
| Chandra | 51,803.6 | 1750 ± 0.104 | ±1430 | 12.8 ± 1.12 | 0.142 [3.82] | 12.8 ± 1.12 | 0.142 [3.82] | 1.16 (22) |
| XMM-Newton | 52,145.1 | 1750 ± 0.104 | ±1430 | 11.7 ± 0.12 | 0.171 [4.60] | 11.7 ± 0.12 | 0.171 [4.60] | 1.16 (47) |
| Chandra | 52,795.1 | 1750 ± 0.104 | ±1430 | 3.1 ± 0.21 | 0.048 [1.30] | 3.1 ± 0.21 | 0.048 [1.30] | 0.95 (25) |
| XMM-Newton | 52,871.2 | 1750 ± 0.104 | ±1430 | 6.9 ± 0.23 | 0.122 [3.27] | 6.9 ± 0.23 | 0.122 [3.27] | 0.96 (49) |

| **O vi Intercombination Line at 21.80 Å** |
| Chandra | 51,803.6 | 1750 ± 0.104 | ±1430 | 19.8 ± 1.16 | 0.110 [2.89] | 19.8 ± 1.16 | 0.110 [2.89] | 1.16 (22) |
| XMM-Newton | 52,145.1 | 1750 ± 0.104 | ±1430 | 15.3 ± 0.52 | 0.100 [2.63] | 15.3 ± 0.52 | 0.100 [2.63] | 1.16 (47) |
| Chandra | 52,795.1 | 1750 ± 0.104 | ±1430 | 13.6 ± 0.50 | 0.159 [4.19] | 13.6 ± 0.50 | 0.159 [4.19] | 0.95 (25) |
| XMM-Newton | 52,871.2 | 1750 ± 0.104 | ±1430 | 16.6 ± 0.56 | 0.156 [4.11] | 16.6 ± 0.56 | 0.156 [4.11] | 0.96 (49) |

| **O vii Forbidden Line at 22.10 Å** |
| Chandra | 51,803.6 | 1750 ± 0.104 | ±1430 | 2.8 ± 0.10 | 0.020 [0.52] | 2.8 ± 0.10 | 0.020 [0.52] | 1.16 (22) |
| XMM-Newton | 52,145.1 | 1750 ± 0.104 | ±1430 | 5.7 ± 0.33 | 0.057 [1.46] | 5.7 ± 0.33 | 0.057 [1.46] | 1.16 (47) |
| Chandra | 52,795.1 | 1750 ± 0.104 | ±1430 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.95 (25) |
| XMM-Newton | 52,871.2 | 1750 ± 0.104 | ±1430 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.0 ± 0.00 | 0.96 (49) |

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8 The Gaussian normalization in units of 10⁻⁵ photons cm⁻² s⁻¹.
9 The reduced Cash statistic and number of degrees of freedom for the fit.
10 The Ne x line width was not well constrained for this observation, and its value was fixed to the weighted average of the values found in the other observations.
11 The Ne xi line widths and velocities were not well constrained for this observation and were fixed to the values found in the Chandra observation of MJD 52,795.1.
12 The O vi line width and velocity were not well constrained for this observation and were fixed to the weighted averages of the values found in the other observations.
13 The O viii line width and velocity were not well constrained for this observation and were fixed to the values found in the XMM-Newton observation of MJD 52,871.2.
The Ne K, Fe L, and O K absorption edges do not appear strong in any of our observations, including the first Chandra observation (ObsID 104) that we analyzed in S01. Therefore, we are no longer able to argue for a significant overabundance of O or Ne in cool circumstellar material, as we suggested in S01. Therefore, this temperature is characteristic of the highly ionized, optically thin outer layers of the accretion disk. We also note that the forbidden lines are absent from the disk. We also note that the forbidden lines are absent from the

\[
\nu_{\text{obs}} = \nu \sin i = \sqrt{\frac{GM_X}{r}} \sin i. \tag{1}
\]

The maximum disk velocity will occur at the inner edge of the accretion disk, which is truncated at the corotation radius of the neutron star at \(\approx 6.5 \times 10^6\) cm. The Keplerian velocity at this radius is \(\approx 5400\) km s\(^{-1}\), whereas the line velocities are measured to be \(\approx 1700\) km s\(^{-1}\) (note that this is the velocity at the center of the Gaussian in the double-Gaussian fits, which is therefore an underestimate of the absolute maximum velocity). If we take this to be the velocity at the inner disk edge, we are able to place a constraint on the inclination angle of the system: \(\sin i \gtrsim 1700/5400 \approx 0.31\) (\(i \gtrsim 22^\circ\)). We may combine this with the previously derived upper limit on the projected semimajor axis, given an orbital period of 42 minutes and limits on the timing noise (Chakrabarty et al. 1997), to find \(3 \lesssim a_X \sin i \lesssim 8\) lt-ms.

The line ratio measurements are indicators of the plasma conditions in the line formation regions. Although we are not able to derive robust limits for the standard diagnostics, we note that the relatively low value of the resonance line (\(r\)) with respect to the intercombination line (\(i\)), \(i/r \approx 2\), suggests that the temperature of the line formation region is \(\gtrsim 10^8\) K (Porquet & Dubau 2000). As discussed in S01, this temperature is characteristic of the highly ionized, optically thin outer layers of the accretion disk. We also note that the forbidden lines are absent from the

### TABLE 5

4U 1626–67 Absorption-Edge Fits

| \(\lambda\) (Å) | Edge | Observatory (ObsID) | Total \(N^a\) (\(10^{17}\) cm\(^{-2}\)) | Implied \(N^b\) (\(10^{17}\) cm\(^{-2}\)) |
|----------------|------|---------------------|------------------------|------------------------|
| 14.3 | Ne K | Chandra (104) | 3.0^{+1.2}_{-0.1} | 2.6^{+0.9}_{-0.8} |
| | | XMM-Newton (0111070201) | 1.9^{+0.1}_{-0.1} | 1.67^{+0.07}_{-0.1} |
| | | Chandra (3504) | 0.9^{+0.0}_{-0.0} | 0.8^{+0.0}_{-0.0} |
| | | XMM-Newton (0152620101) | 1.2^{+0.4}_{-0.3} | 1.0^{+0.4}_{-0.4} |
| 17.5 | Fe LIII | Chandra ObsID 104 | 0.6^{+0.3}_{-0.1} | 0.17^{+0.08}_{-0.06} |
| | | XMM-Newton (0111070201) | 1.3^{+0.1}_{-0.1} | 0.37^{+0.09}_{-0.1} |
| | | Chandra (3504) | 0.5^{+0.1}_{-0.0} | 0.13^{+0.05}_{-0.05} |
| | | XMM-Newton (0152620101) | 1.2^{+0.3}_{-0.1} | 0.34^{+0.09}_{-0.09} |
| 23.3 | O K | Chandra ObsID 104 | 1.2^{+0.3}_{-0.1} | 0.9^{+0.2}_{-0.2} |
| | | XMM-Newton (0111070201) | 1.3^{+0.2}_{-0.1} | 0.7^{+0.3}_{-0.2} |
| | | Chandra (3504) | 1.7^{+0.0}_{-0.0} | 0.8^{+0.3}_{-0.2} |
| | | XMM-Newton (0152620101) | 1.3^{+0.0}_{-0.0} | 0.8^{+0.3}_{-0.2} |

| \(N^a\) | Fitted value of \(N^a\) with the tbnew model (J. Wilms et al. 2007, in preparation) and fitting over the immediate range of the absorption structure, restricting the continuum components to remain within their 90% confidence intervals (see text).

| \(N^b\) | Value of \(N^b\) implied by the fitted \(N^a\), assuming ISM abundances presented in Wilms et al. (2000).

### TABLE 6

Pulse Period of 4U 1626–67

| Date       | MJD     | Pulse Period (s) | Observatory |
|------------|---------|-----------------|-------------|
| 2000 Sep 16 | 51,803.6 | 7.6726(2)       | Chandra     |
| 2001 Aug 24 | 52,145.1 | 7.6736(2)       | XMM-Newton  |
| 2003 Jun 5  | 52,795.1 | 7.67514(5)      | Chandra     |
| 2003 Aug 20 | 52,871.2 | 7.67544(6)      | XMM-Newton  |

### FIG. 5

Frequency history of 4U 1626–67. Top: All data. Bottom: Expanded view of the Compton BATSE through the Chandra and XMM-Newton observations, along with the BATSE prediction (solid curve with dot-dashed errors). Pulse frequency data from other observatories, as well as the BATSE prediction, can be found in Chakrabarty et al. (1997, 2001).
He-like triplets. This could be due to several effects (see, e.g., Blumenthal et al. 1972; Porquet & Dubau 2000). For example, if the line formation region has relatively high density ($n_e \approx 10^{12} \text{ cm}^{-3}$), collisional excitation would cause many electrons in the upper level of the forbidden line state to transition into the upper levels of the intercombination line states ($^3S_1 \rightarrow ^3P_0; ^3P_1; ^3P_2$), suppressing the forbidden line emission. Alternatively, the excitation could be due to ultraviolet photons produced in the accretion disk. To determine the relative importance of these two effects, one would need to perform detailed modeling of the accretion disk emission and line formation regions, which is beyond the scope of this paper.

5.3. Long-Term Flux Evolution

X-ray observations of 4U 1626–67 show that it has been decreasing in flux since 1977. Since this decrease appears to be bolometric—there is no sign of variable absorption, and the continuum spectrum is known to have undergone only one major change—we may use the X-ray flux to help determine other characteristics of the system. The long-term trend can be described by either an exponential decay or a linear decrease (see Fig. 2). If we take it to be logarithmic and integrate over the duration of the outburst, the fluence is $0.927 \text{ ergs cm}^{-2}$ [giving a total energy of $1.1 \times 10^{44} \left( d_{\text{kpc}}^2 \right) \text{ ergs}$]. Converting this to an average accretion rate, we find that

$$\dot{M}_{\text{ave}} \approx 2.2 \times 10^{-10} \frac{\Delta t_{\text{yr}}^{-1}}{d_{\text{kpc}}^2} M_\odot \text{ yr}^{-1},$$

where $\Delta t_{\text{yr}}$ is the time between outbursts in years and $d_{\text{kpc}}$ is the distance to the source in kpc. If we assume that the source is persistent and take $\Delta t \approx 30 \text{ yr}$, we find that $d \approx 2 \text{ kpc}$, which is less than the minimum distance of 3 kpc derived from considerations of the accretion torque during spin-up (Chakrabarty et al. 1997). If we assume a distance of $\geq 3$ kpc, and take the long-term average accretion rate to be $\dot{M}_{\text{GR}} = 3 \times 10^{-11} M_\odot \text{ yr}^{-1}$ (the value from gravitational radiation–driven orbital evolution with a white dwarf donor; see Chakrabarty 1998), we find that $\Delta t \geq 70 \text{ yr}$, significantly longer than the known duration of the current outburst.

We may also combine current theory on disk stability with the flux data for 4U 1626–67 to obtain constraints on its distance and possible outburst duration. The accretion disk temperature will be determined both by viscous heating as well as X-ray heating from the central source (see, e.g., King et al. 1996; van Paradijs 1996), yielding a temperature profile of

$$T^4 = \frac{\eta \dot{M} c^2 (1 - \beta)}{4 \pi \sigma r^2} \left( \frac{dH}{dr} - \frac{H}{r} \right),$$

Fig. 6.—Folded pulse profiles of 4U 1626–67 from the XMM-Newton pn, ObsID 0111070201.

Fig. 7.—Same as Fig. 6, but for ObsID 0152620101.
where $\eta$ is the efficiency of the conversion of rest-mass energy into X-ray heating, $\beta$ is the X-ray albedo of the disk, $H$ is the scale height of the disk, and $r$ is the Stefan-Boltzmann constant. Following King et al. (1996) we take $\eta = 0.11$, $\beta = 0.9$, assume that $H/r \approx 0.2$ is constant, and that $H \propto r^n$, where $n = 9/8$ for shallow heating, which we would expect to dominate in this system. The disk stability criterion is that the temperature at the outermost disk radius remain $\geq 6500$ K (Smak 1983).

Setting $r = r_{\text{out}} \approx 2 \times 10^{10}$ cm, we derive a critical accretion rate of $\dot{M} = 3.6 \times 10^{-12} M_\odot$ yr$^{-1}$. Note that this is lower than the value of $M_{\text{crit}}$ quoted above. Assuming that the accretion rate is directly proportional to the flux, and that it remained above the critical rate throughout the current outburst, we find the distance to 4U 1626−67 to be $\gtrsim 0.6$ kpc. Furthermore, if we assume a distance range of 3−13 kpc and an exponential (or linear) decline in flux commensurate with the current trend, we find that $\dot{M} \lesssim M_{\text{crit}}$ in the range 2018−2020 (or 2008 June−September).

We therefore expect 4U 1626−67 to become quiescent within 2−15 yr.

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