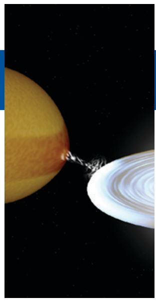

Timing Studies of X-ray Binary Orbits

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X-ray astronomy, by necessity, involves the study of highly variable stars, nearly all of them in binary systems where one member is a compact object such as a neutron star or black hole. These systems allow us to probe physical effects in regions of extreme gravity, high temperatures, and intense magnetic fields that are characteristic of compact objects and are unattainable in laboratory experiments. By studying the brightness variations and eclipses using space-based X-ray telescopes, we can determine the binary system orbital parameters and characteristics of the mass transfer that powers these variations. This, in turn, allows us ultimately to understand better the evolution of these exotic binary systems. Here we describe two such studies carried out at NRL: the discovery of the orbit of a neutron star orbiting a hot supergiant star, and the surprising orbital period evolution observed in a low-mass X-ray binary.

INTRODUCTION

The night sky viewed with your eyes is a peaceful place, with thousands of point-like stars shining at the same brightness night after night, year after year. Each star is powered by nuclear reactions at its core. These keep the surface hot for millions or billions of years, with nearly all of the energy being emitted at visible wavelengths. Viewing the sky in X-rays is a completely different experience. Nearly all X-ray sources are highly variable, changing brightness and color by large amounts on timescales ranging from milliseconds to millennia. The fundamental reason for this dramatic behavior is that the power source of these celestial X-ray sources is the accretion of matter onto a compact object (a white dwarf, neutron star, or black hole). The compact object in an X-ray binary *in isolation* would emit very little radiation because it has no internal source of heat and, in the case of a black hole, doesn't even have a surface from which to emit! However, if the object is in a binary system with a more normal star it can accrete matter captured either from the stellar wind of the companion or from matter overflowing the equipotential surface called the Roche lobe (Fig. 1). This material typically has a relatively large angular momentum and thus forms an accretion disk around the compact object as it loses energy via viscosity. As this matter falls into the deep potential well of the compact object, it releases an enormous amount of energy and is heated to extreme temperatures (~10^7 K) where X-rays are the dominant radiation emitted.

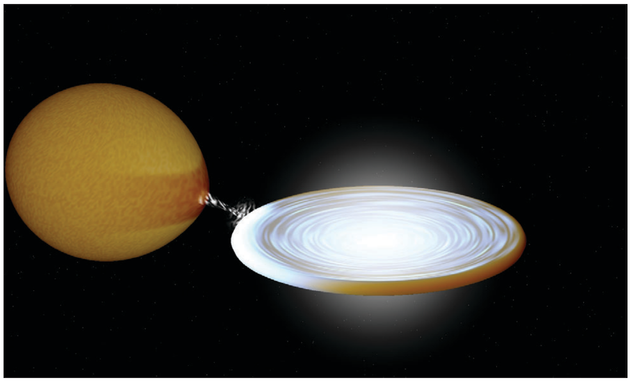

FIGURE 1
Artist's conception of an X-ray binary system. The large star is dumping matter into the accretion disk, and that matter is spiraling inward toward the compact object and heating up. In the central regions of the disk, the temperatures are millions of degrees and the orbital timescales are milliseconds. The thin fuzz above the disk represents an optically thin corona of very hot plasma, which can radiate high-energy X-rays and gamma-rays via the inverse-Compton process. (Illustration created with the binary visualization tool BinSim 0.8 by R. Hynes.)

These X-ray binary systems make wonderful laboratories for studying the physics of matter in extreme conditions and for understanding complex stellar and binary evolution. They also have several

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potential applications of relevance to the Navy. These systems exhibit numerous properties that are of great interest and are difficult or impossible to recreate in a laboratory, including magnetic field strengths of up to 10^{14} gauss, matter at super-nuclear densities, rotational periods as short as 1.5 ms, strong gravity effects predicted by Einstein's general theory of relativity, magneto-hydrodynamic effects, relativistic jet acceleration, and more. However, since X-rays cannot penetrate the Earth's atmosphere, we must study them from instruments flown on rockets or satellites.

NRL was among the early pioneers of X-ray astronomy, beginning with Dr. Herbert Friedman's experiments flown on V-2 rockets captured during World War II. NRL has been highly active in the field ever since, flying numerous sounding rockets and serving as principal investigator institution for several satellite instruments, including HEAO A-1, Spartan 1, and the USA Experiment. The Navy initially contributed to the exploration of the X-ray sky to understand natural backgrounds relevant to any possible DOD systems operating in space. As understanding of these unusual celestial sources improved, their value as physics laboratories was appreciated. They can be used, for example, to test hydrodynamics codes in regimes of high temperature, density, and magnetic field strength well beyond laboratory conditions. By now, other kinds of applications are under study, such as the use of celestial X-ray sources to support autonomous satellite operations and navigation in what amounts to a passive GPS-like system.

X-ray binaries are typically classified by the type of compact object they contain and the mass of the companion star. Compact objects are the final stage in the lifecycle of stars. When their nuclear fuel is exhausted, the core of a star collapses until it is supported by some pressure force. Stars similar to our Sun collapse into *white dwarfs* that compress the mass of the Sun into an object the size of the Earth and are supported by electron degeneracy pressure. This pressure is the result of the fact that electrons are fermions and are thus subject to the Pauli Exclusion Principle, which prevents more than two fermions from occupying the same volume. More massive stars can overcome this pressure and collapse into neutron stars that reach densities far above those found in an atomic nucleus and are supported by neutron degeneracy pressure. Neutron stars have a mass of 1.4 times the mass of our Sun and a radius of only 10 km! The collapse of the most massive stars cannot even be stopped by neutron degeneracy pressure and thus they continue collapsing all the way to a *black hole*, an object so compact and massive that even light cannot escape. When one of these stars is orbiting a massive normal star (often about 10 times the mass of our Sun), the system is referred to as a High-Mass X-ray Binary (HMXB). When the companion is a low-mass star (typically a fraction of the mass of our Sun), the system is called a Low-Mass X-ray Binary (LMXB). The two types of systems are the result of different paths of stellar evolution and, in general, the HMXB systems tend to be younger and contain slowly spinning, highly magnetized neutron stars, while the LMXBs are extremely old and are the progenitors of the millisecond radio pulsars.

The two instruments used in the work described here are NASA's Rossi X-ray Timing Explorer (RXTE) and the Unconventional Stellar Aspect (USA) Experiment. RXTE was launched in December 1995 and carries three instruments, the primary being the Proportional Counter Array (PCA), an array of five xenon proportional counters sensitive to X-rays in the 2 to 60 keV energy range. The USA Experiment aboard the Advanced Research and Global Observation Satellite (ARGOS) was launched in February 1999 and operated until November 2000. USA was built by NRL in collaboration with Stanford University for the dual purposes of doing X-ray astrophysics and exploring several applications of Navy interest. USA consisted of two argon/methane proportional counters sensitive to X-rays in the 1 to 15 keV energy range. During its operating lifetime, USA acquired substantial observing time on about 60 bright X-ray sources, including transient black hole systems, X-ray pulsars, active galactic nuclei, and a variety of bright LMXBs. USA was also designed to conduct experiments in the application of X-ray sources to satellite autonomy, as described above.

In this article, we review two projects whose results were published this year. First, we describe the discovery of the orbit of an accreting pulsar with a supergiant companion, and then we describe the detailed study of the orbital evolution of a nonpulsing neutron star that is eclipsed by its companion.

DISCOVERY OF THE ORBIT OF A SUPERGIANT X-RAY BINARY

Accreting X-ray pulsars are X-ray binary systems (most often high-mass X-ray binaries) where the compact object is a highly magnetized neutron star. The surface magnetic field can be 10^{12} G or higher (for comparison, the magnetic field at the surface of the Earth is about 0.5 G). This strong magnetic field channels the accretion flow inside of a radius where the magnetic pressure overwhelms the ram pressure of the flow (called the Alfvén radius). This channeled flow accretes in columns onto the neutron star surface at the polar caps. As these hot polar cap regions rotate with the spin of the neuron star (assuming that the magnetic axis is not perfectly aligned with the rotational axis), we view them with periodically varying geometry. This causes the observed X-ray flux to be modulated at the spin period. These pulsations allow us to determine the spin rate of the neutron star to very high precision. This, in turn, allows precise determinations of the torque exerted on the neutron star by the accreting matter. It allows determination of the orbital parameters because of the Doppler shift of the pulse frequency as the pulsar travels in its orbit. In this section, we describe how a study of the X-ray pulsations in one particular system resulted in the discovery of the orbit of that system. This work was done in collaboration with Prof. Deepto Chakrabarty of the Massachusetts Institute of Technology.[1]

It is a remarkable coincidence that there are two unrelated X-ray pulsars in Centaurus with nearly identical spin periods separated by only 15 arcminutes on the sky. One of the sources is the 292-s transient X-ray pulsar 2S1145–619, which is associated with the main sequence Be-type companion Hen 715 and is about 5,000 light-years distant. The pulsar exhibits periodic outbursts at 186.5 d intervals, which are believed to occur during periastron passage in the neutron star's eccentric orbit. The X-ray flux in quiescence is typically about 3 mcrab, but the flares near periastron can reach a flux of several hundred mcrab. (A millicrab (mcrab) is a commonly used unit of X-ray flux equal to 1/1000th of the flux of the Crab Nebula, the brightest steady X-ray source in the sky.)

The second source, which is the subject of this study, is a 297-s X-ray pulsar designated 1E1145.1–6141 that is associated with a B-type supergiant companion (V830 Centaurus). Until our study, this source had a rather sparse observational history and an unknown orbital period, despite being a persistent X-ray pulsar and one of only 10 X-ray pulsars with massive supergiant companions. Studies of the companion star with ground-based optical telescopes suggested orbital periods ranging from 5.6 to 12.1 days, but these studies had not produced a definitive result. A binary period of at least 6 days is required for the neutron star's orbit to be outside the surface of the companion star so a measurement of the orbital parameters of the system was of considerable interest. In addition, a supergiant-neutron star binary with an orbital period less than 20 days has a significant a priori probability of exhibiting an X-ray eclipse. Eclipsing pulsars provide important constraints on the masses of accreting neutron stars, and only eight such systems are currently known. Thus motivated, we observed 1E1145.1–6141 with RXTE in an effort to determine the pulsar's orbital period and search for X-ray eclipses.

Observations

We observed the 1E1145.1-6141 system 80 times at four different epochs between June 1997 and February 2000 using the Proportional Counter Array (PCA) on RXTE. The PCA collects X-ray photons in the 2 to 60 keV range and records the arrival time (1-μs resolution) and energy (129-channel resolution) of every detected photon. Because the PCA has a 1° field of view and no imaging capability, each of the observations was scheduled to occur far from periastron passages of the 2S1145–619 system so that its flares would not contaminate the measurement. It is important to note that nonimaging observations can only resolve the coherent pulsations of 1E1145.1–6141 (297 seconds) and 2S1145–619 (292 seconds) into separate Fourier bins for observation lengths greater than 20,000 s. A few of our observations were this long and we were able to determine that when 2S1145–619 was not flaring, it did not interfere significantly with observations of 1E1145.1–6141.

Timing Analysis

To measure the pulse period of 1E1145.1–6141 precisely and search for delays caused by the pulsar moving in its orbit, we performed a pulse time-of-arrival (TOA) analysis. For each short observation, we selected all of the photons in the 2 to 10 keV energy range, converted them to an inertial reference frame at the solar system center of mass (this process, known as barycentering, removes the effects of the motion of the spacecraft and the Earth from the data), and folded them into an average pulse profile by calculating their phase with respect to a nominal pulse period of 296.65 s. Figure 2 shows a typical pulse profile. From each profile, a TOA is measured by cross-correlation with a high signal-to-noise template profile that defines phase zero.

If a pulsar is pulsing at a constant period and not moving in an orbit, each pulse will arrive an integer number of pulse periods after the first. So, to search for effects of an orbit, we compare the measured arrival times to a simple model with a constant pulse period at each epoch: $T_n = T_0 + P \times n$, where T_n is the arrival time (TOA) of the nth pulse and P is the pulsar period. Figure 3 shows the results of this comparison for each of the four observing epochs. Astronomical times are often reported using the Julian Day (JD) system, which measures days since noon on January 1, 4713 BC. Modified Julian Day (MJD) is defined as JD-2,400,000.5, which shortens dates near the present to five digits and subtracts an extra half day so that the day begins at midnight as it does in civil time. As an example, MJD 51544 is January 1, 2000.)

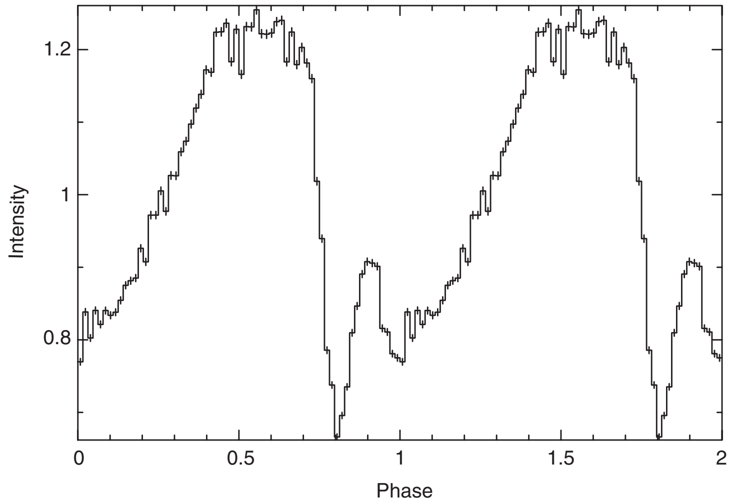

FIGURE 2
A folded light curve (pulse profile) of 1E1145.1–6141 with 64 bins across the 296.65-s period. For clarity, two cycles are shown. The intensity is the 2–10 keV X-ray flux relative to the average flux, indicating that about 20% of the emission is pulsed.

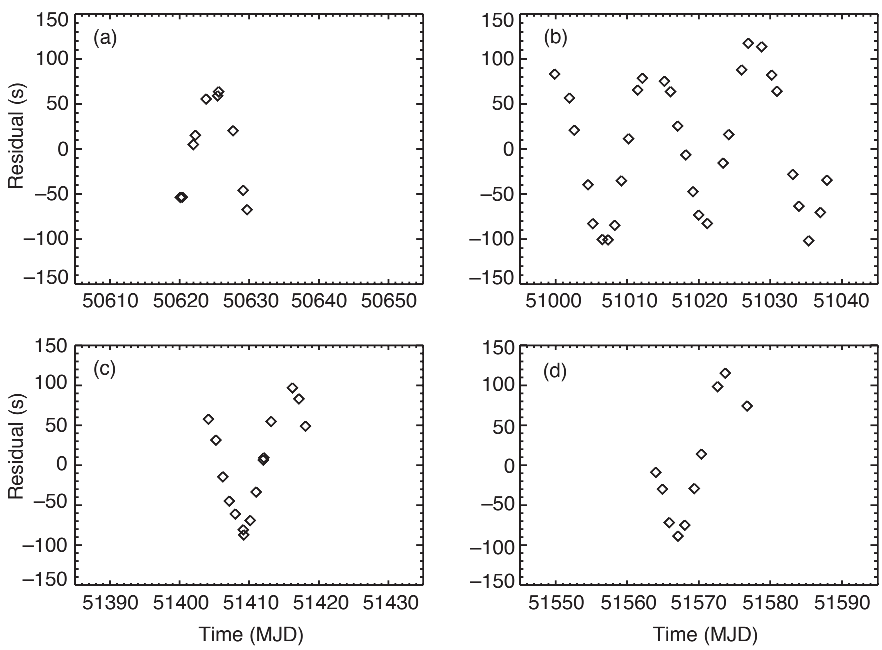

FIGURE 3
Pulse arrival time residuals from a constant-period model for each of the four observation epochs of 1E1145.1–6141.

Clearly, orbital effects are present. A roughly sinusoidal pattern is seen in each set of residuals, with a period of about 14 days. In such a plot, the pulses arrive late when the pulsar is behind its companion (farther from the Earth) and early when the pulsar is in front of its companion. The total observed delay immediately reveals that the projection of the orbit in the direction of Earth has a radius of about 100 light-seconds. This is about one fifth the size Earth's orbit around the Sun.

A much more precise determination of the orbital parameters is possible by fitting a timing model that includes a Keplerian orbit in addition to the spin of the pulsar. We first determined the orbital period by using the measured minima in the arrival time residuals in Fig. 3. Assuming a constant orbital period P_{orb}, these five minima must be separated by integer multiples of P_{orb}. The best-fit orbital period determined in this way is $P_{orb} = 14.37 \pm 0.02$ days.

To derive the remaining binary parameters and refine the orbital period determination, the effects of the binary motion must be decoupled from intrinsic changes in the pulsar's spin due to accretion torques. We performed a combined fit of all the arrival time measurements shown in Fig. 3. Because of the effect of accretion torque during the time between observations, we could not produce a fully phase-connected orbital fit. Instead, we used a model in which the frequency and phase of the pulsar were allowed to jump discontinuously between each epoch of observation and the orbital parameters applied globally. Other than the orbital effects, the pulse frequency was held constant within each epoch.

Table 1 lists our best-fit orbital parameters, and Fig. 4 shows the resulting model with all data folded at the orbital period. The five parameters in Table 1 are the standard Keplerian orbital parameters for an eccentric binary orbit: P_{orb} is the orbital period measured in days, T_0 is the epoch at which the neutron star crosses orbital phase 0 measured in MJD, $a_x \sin i$ is the projected semi-major axis of the orbit measured in light-seconds, e is the orbital eccentricity, and ω is the longitude of periastron, which describes where in the orbit the neutron star is closest to the companion star. The errors quoted in Table 1 are statistical only; any biases introduced by unmodeled accretion torques are not included. However, these systematic effects should be quite small since the data cover more than six cycles of the binary orbit and such effects are expected to average out.

Table 1. Orbital Parameters of 1E1145.1-6141

Parameter	Value
P_{orb}	14.365 ± 0.002 d
T_0 (MJD)	51008.1 ± 0.4
$a_x \sin i$	99.4 ± 1.8 light-s
e	0.20 ± 0.03
ω	–52° ± 8°

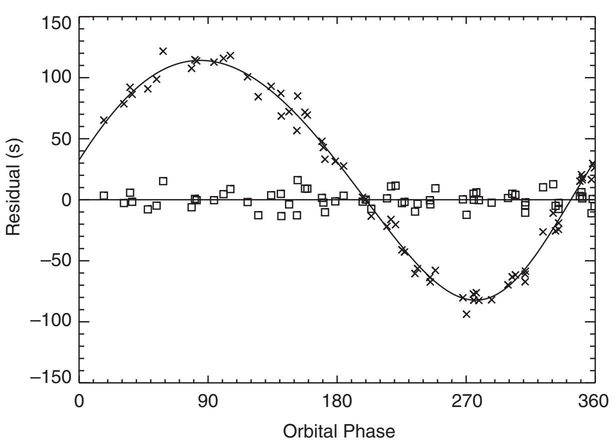

FIGURE 4
Observed pulse arrival time residuals to a constant-period model (crosses) with the best-fit eccentric orbit solution overplotted as a solid line. The squares are the same data after the orbit model is subtracted.

With the orbit determined, we can measure the precise intrinsic pulse period at each epoch with the contaminating effects of the orbit removed. Figure 5 shows these determinations along with all historical period measurements of this source. The pulsar has shown significant spin up since its discovery in 1978. Fitting the frequencies to a straight line yields an average frequency derivative of 1.2×10^{-14} Hz/s, which implies a spin-up timescale of 1000 years. This is similar to other supergiant X-ray pulsars.

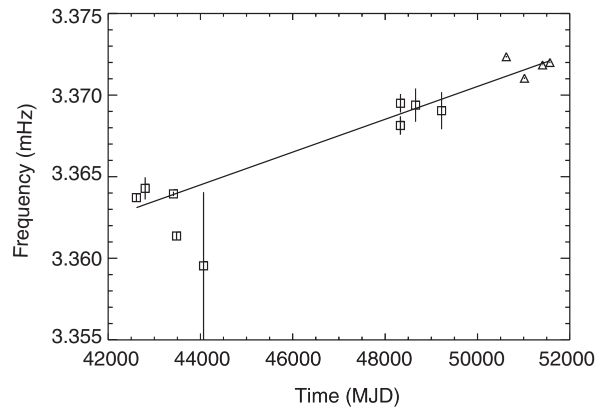

FIGURE 5
Barycentric pulse frequency as a function of time for 1E1145.1–6141. Squares are previously published data points, and the triangles are the data from our RXTE observations.

Discussion

This new discovery adds to the number of well-determined orbits in X-ray binary systems. In the search, we found no convincing evidence for X-ray eclipses, although the pulsar was not detected in one observation. Further X-ray observations of this source are underway. Also, optical studies of the Doppler shifts of spectral lines from the companion star could potentially provide further constraints on the orbit and the mass of the neutron star (as has been possible in a few other binary systems to date).

LONG-TERM TIMING OF AN LMXB ORBIT

We now turn to the second investigation, which involves precise timing of the eclipses of the LMXB EXO0748–676.[2] The physical process that drives the accretion in low-mass X-ray binary systems is not known with any certainty. The accretion may be driven by the loss of angular momentum through gravitational radiation or magnetic braking, or by the nuclear evolution of the secondary, which causes it to overflow its Roche lobe. The mass transfer from the secondary can be either conservative (meaning that all mass lost by the secondary eventually ends up on the neutron star) or nonconservative. Models incorporating these physical processes make specific predictions for the rate at which the binary orbital period (P_{orb}) changes. For instance, the orbital period of an LMXB undergoing conservative mass transfer at a typical rate of 10^{-10} to 10^{-8} solar masses per year from a Roche-lobe-filling 1 solar mass companion is expected to decrease with a timescale of 10^8 to 10^{10} years. Unfortunately, none of the published orbital period derivative measurements in LMXBs are in agreement with theoretical expectations!

Six LMXBs are currently reported to have observed orbital period derivatives. Three of these systems (X1820–303, X1658–298, and Her X-1) have apparently negative period derivatives, indicating that the orbital separation is shrinking. The other three systems (X1822–371, X2127+119, and EXO0748–676) have positive orbital period derivatives, implying that the binary orbital separation is increasing. In each of these systems, the orbital period appears to be evolving at a considerably faster rate (by a factor of 10 or more) than theoretical predictions for a system undergoing conservative mass transfer. Clearly, the theoretical understanding of the processes driving orbital evolution of LMXBs is still very poor.

The best systems for addressing this problem are the eclipsing LMXBs, which are in an orientation so close to edge-on that the X-rays from the neutron star are eclipsed by the companion once per orbit as the companion passes between the neutron star and the Earth. Only three LMXBs are known to show full eclipses. Full, sharp eclipses are important since the observed beginning of eclipse (ingress) and end of eclipse (egress) give precise timing markers that can be used to study the evolution of the orbit. The best candidate for such a study is the LMXB EXO0748–676, which is relatively bright in X-rays and has been persistently visible for the last 20 years, while the other known eclipsing LMXBs are transient systems and are faint or not visible much of the time. Thus motivated, we began a detailed long-term study of EXO0748–676 to greatly increase the observational data on LMXB orbital period evolution. This was made possible recently by the fact that the RXTE and USA instruments had very flexible automated scheduling. This allows many short observations of the source for the purpose of making repeated eclipse measurements over a long period of time without using a large amount of satellite observing time.

Eclipse Timing Observations

We observed EXO0748–676 with both RXTE and USA beginning in 1996 and continuing to the present time. EXO0748–676 exhibits complete eclipses that last about 500 seconds out of each 3.82-hour binary orbit. (Figure 6 shows an example of an eclipse observation along with a fit to the observed eclipse

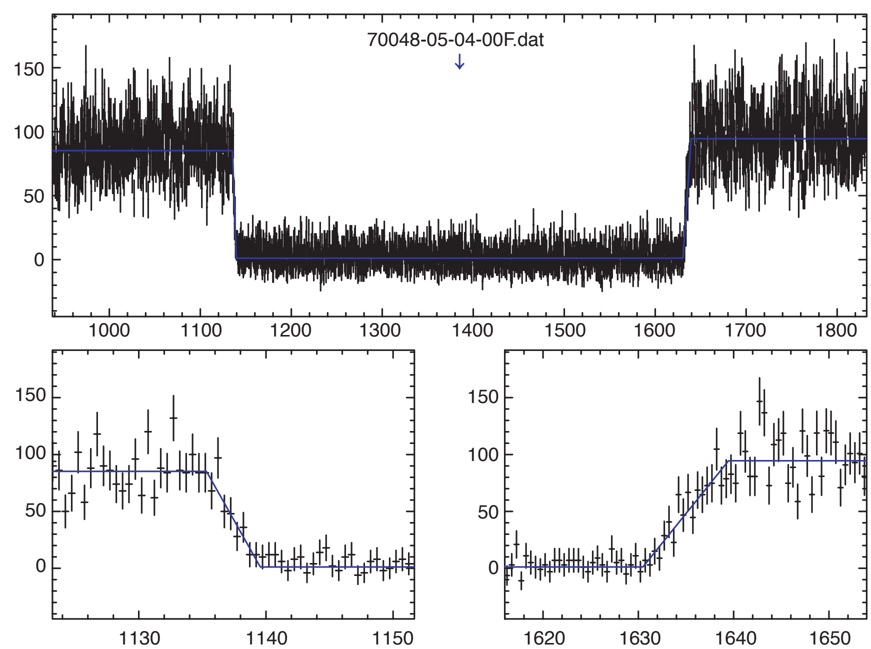

FIGURE 6
Sample eclipse observation of EXO0748–676. The lower plots are detailed views of the ingress and egress regions. The solid line represents the piecewise-linear model used to fit the eclipse, and the arrow marks the best-fit mid-eclipse time.

profile.) Typically, we observed 5 to 6 consecutive eclipses once every two months. The data are processed by selecting photons in the 2 to 8 keV energy range, converting the observed times to the arrival time at the solar system barycenter, binning the data into 0.5 s bins, and subtracting a background model. This results in a clean eclipse light curve for each observation. These light curves are then fitted to a model eclipse profile (a piecewise linear ramp-and-step model) to determine the precise time of mid-eclipse. Most observations result in a mid-eclipse time determination accurate to about 0.5 seconds. The mid-eclipse time is chosen as the most stable orbital phase marker because the eclipse ingress time, egress time, and total duration vary significantly from eclipse to eclipse, possibly due to changes in the structure of the companion star's atmosphere.

To analyze the eclipse timing data, we compare the observed times to those that would be calculated by a simple model in which the eclipses occur at a constant period. This is called an observed minus calculated or "O–C" plot, and Fig. 7 shows all of the RXTE and USA data on such a plot. Clearly, the data are not consistent with a simple constant period, and the observed variations are considerably larger than the measurement error. This is shown by the error bars on the plot. In addition, no simple model of orbital period evolution significantly improves the fit. The solid line is the best fit model with a constant period derivative, $\dot{P}_{orb} \equiv dP_{orb}/dt$, and also yields a very poor fit. Apparently, some other process is at work, causing the observed eclipse phases to do a random walk about a smooth solution. This problem is even more apparent when all the historical eclipse measurements are added to the plot, as seen in Fig. 8. No matter what simple model is chosen, extremely significant residuals remain.

Intrinsic Period Jitter

To model this random walk, we added a term to account for small, random (zero-mean) fluctuations of the orbital period around the true underlying orbital period. This results in a cumulative random walk in orbital phase as seen in our measurements. If the underlying orbital period evolution is known, the O–C residuals can be represented as

$$(O-C)_j = \sum_{i=1}^{N_j} \varepsilon_i + e_j,$$

where ε_i is a random, zero-mean fluctuation in the length of orbit period i, and e_j is the measurement error in the jth mid-eclipse time. The cumulative nature of the ε_i causes the systematic wandering of the mid-eclipse residuals apparent in Fig. 7. We performed a maximum-likelihood analysis of the residuals to determine whether such a process could account for the observations and what the magnitude of the ε and e terms were (called σ_ε and σ_e, respectively). Looking at the RXTE and USA data only (Fig. 7), we found that such a model fit well with a period jitter σ_ε of 0.12 seconds and a measurement error σ_e of 1.62 seconds. When we extend this analysis to the full data set in Fig. 8, we find that a model that includes an intrinsic orbital period derivative plus intrinsic period jitter is preferred to one with period jitter alone.

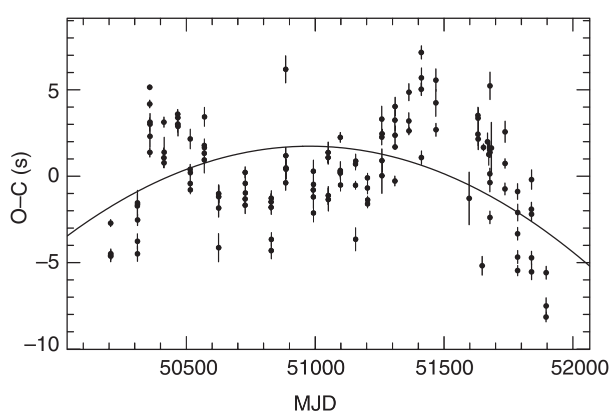

FIGURE 7
O–C plot of mid-eclipse times of EXO0748–676 measured with RXTE and USA. The residuals show a random walk about the constant-period model. The solid line is the best-fit model with constant period derivative (which is still a very poor fit).

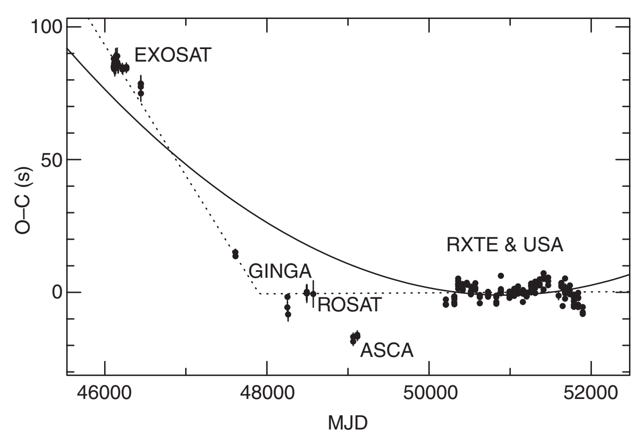

FIGURE 8
O–C plot of all published eclipse timings of EXO0748–676, including data from five different satellites from 1985 to the present day. The solid line is the best-fit model with constant period derivative, and the dotted line is a model with a sudden change in orbital period.

This random jitter has caused quite a bit of confusion over the last 20 years in interpreting eclipse timings of EXO0748–676. Previous authors, looking at small samples of data, have variously concluded that the orbital period is constant, increasing, decreasing, or sinusoidally varying. The maximum-likelihood analysis combined with the large and well-sampled data set we acquired allow us to begin to separate the random jitter from the longer-term orbital period evolution and rule out a number of these models.

We verified our result with a Monte Carlo technique in which we simulated a system with a period jitter of 0.12 seconds but no underlying orbital period evolution. We generated many simulated data sets and sampled them with the same sampling times as the real observations. These data sets demonstrated that spurious positive or negative period derivatives could easily be created by the random walk process. However, a random walk with a magnitude of 90 seconds, as seen in Fig. 8, was extremely unlikely. We therefore conclude that in the EXO0748–676 system there is both period jitter and orbital period evolution with a magnitude of

$$\dot{P}_{orb} = 1.2 \times 10^{-11}.$$

This corresponds to an orbital period evolution timescale of about 40 million years, whereas the timescale expected from the amount of mass moving around the system is more like a billion years.

Discussion

Based on our analysis, we conclude that the orbital period of EXO0748–676 has increased by ~8 ms over the past 16 years. This measured $\dot{P}_{\mathrm{orb}}$ implies that the two stellar components are moving away from each other instead of toward each other, as current theoretical models indicate they should and at a rate much faster than expected. Furthermore, the intrinsic period jitter that we see is certainly not expected from previous theoretical work. This jitter may correspond to very large changes in the orbital angular momentum over very short timescales, much too short to be explained by changes in the rate at which the companion is losing mass. So, we are forced to look for other explanations for the jitter. One possible reservoir of angular momentum is the rotating companion star. The jitter could be due to exchange of angular momentum between the orbit and internal modes in the companion star. These internal mode changes might be associated with shape changes in the companion star and thus might be able to be probed by a careful analysis of the eclipse profiles. Probing internal dynamics of Sun-like stars is a challenge that astronomy is only now beginning to take on. X-ray eclipse methods in close binaries, where the Sun-like companion star is subject to extreme stresses, could complement information obtained in other ways such as helioseismology.

CONCLUSIONS

The X-ray astronomy group at NRL continues to make use of instruments constructed in-house as well as facilities provided by NASA and the international community to study the population, characteristics, and evolution of a wide variety of cosmic X-ray sources. Future plans include the use of next-generation X-ray telescopes that incorporate solid-state detectors, which are lighter and far more durable than gas-based detectors. These designs will be much closer to a package that can realistically be used for autonomous satellite navigation and timekeeping using celestial X-ray sources. Careful studies of the behavior of the celestial clocks like pulsars and eclipsing binaries will provide the raw data on which such a system will be based.

[Sponsored by ONR and NASA]

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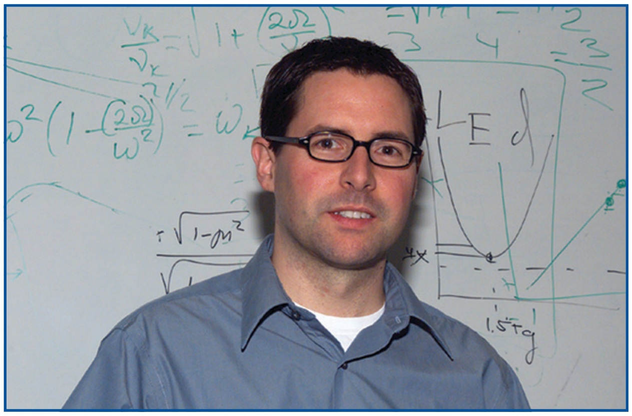
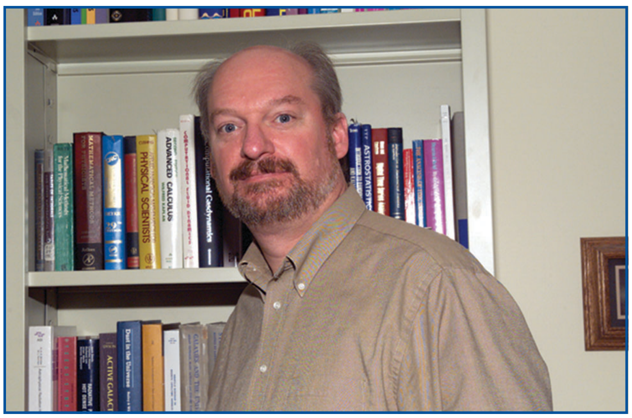
THE AUTHORS



PAUL S. RAY graduated from the University of California, Berkeley in 1989 with an A.B. degree in physics. He received a Ph.D. in physics from the California Institute of Technology in 1995 where his thesis research involved high-sensitivity searches for radio pulsars. He came to NRL in 1995 as an NRC-NRL postdoc jointly in the Space Science Division and the Remote Sensing Division and became a member of the NRL staff in 1997. His research centers on the astrophysics of compact objects, particularly accreting binaries and radio pulsars in our Galaxy. His studies have ranged over the electromagnetic spectrum from the longest radio wavelengths to high-energy gamma rays. He is a member of the NASA RXTE User's Group, has authored or co-authored 18 articles in refereed scientific publications, and has been awarded an Alan Berman Research Publication Award.



MICHAEL T. WOLFF received his B.S. degree from the University of Maryland in 1977 and his Ph.D. in astronomy from Indiana University in 1985. He has worked at the Naval Research Laboratory since 1986, first as a Universities Space Research Association Visiting Scientist until 1991 and then as a civil servant. His research activities have included the hydrodynamic modeling of high-temperature accreting plasmas in magnetic cataclysmic variable systems, participating in the design, construction, testing, and then commanding of the USA X-ray timing experiment that orbited the Earth as part of the U.S. Air Force ARGOS mission, and investigated the properties of a wide range of compact object binary systems including white dwarf, neutron star, and black hole systems. He currently works in the High-Energy Space Environment Branch in NRL's Space Science Division.

KENT S. WOOD received his B.S. degree from Stanford University in 1967 and his Ph.D. from the Massachusetts Institute of Technology in 1973. He came to NRL in 1973 and has remained here to the present time. He worked on the HEAO A-1 Experiment, a mission to map the brightest sources in the X-ray sky. Since then, his work has centered on the study of compact objects such as neutron stars and black holes, using mainly X-ray timing methods. He is the Principal Investigator for the USA Experiment on ARGOS, which has conducted timing studies and explored applied uses of X-ray astronomy and computing in space. He is co-investigator on the GLAST mission, a NASA gamma-ray facility being prepared for launch. He is Head of the X-ray/UV Astrophysics and Applications Section in the High-Energy Space Environment Branch at NRL.

PAUL HERTZ was an astrophysicist in the Space Science Division from 1985 to 2000. During that time his primary research interests were X-ray binaries, although his work ranged from globular clusters and supernova remnants to gamma ray bursts. He also coordinated NRL's participation in NASA guest investigator programs and pioneered the use of the NRL Connection Machine for the analysis of astrophysical data. Dr. Hertz received a B.S. in physics and mathematics from the Massachusetts Institute of Technology and a Ph.D. in astronomy from Harvard University. He has been awarded the Alan Berman Research Publication Award twice, and was awarded the 1985 Robert Trumpler Award of the Astronomical Society of the Pacific. Since 2000, Dr. Hertz has been a Senior Scientist in the Office of Space Science, NASA Headquarters, Washington, DC.