ISTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

OBSERVATIONAL CONSTRAINTS ON THE TORQUE ACTING ON ACCRETING PULSARS

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KÜTLE AKTARIMI YAPAN PULSARLARDA TORKUN GÖZLEMSEL OLARAK KISITLANMASI

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GÖKÇE ÖZSÜKAN, a M.Sc. student of ITU Institute of Science and Technology 509131105 successfully defended the thesis entitled **"OBSERVATIONAL CONSTRAINTS ON THE TORQUE ACTING ON ACCRETING PULSARS"**, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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FOREWORD

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May 2015 GÖKÇE ÖZSÜKAN

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ABBREVIATIONS

LMXB **:** Low-mass X-ray binary
HMXB **:** High-mass X-ray binary
GL **:** Ghosh & Lamb
MTD **:** Magnetically treated disk
MJD **:** Modified Julian date

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OBSERVATIONAL CONSTRAINTS ON THE TORQUE ACTING ON ACCRETING PULSARS

SUMMARY

X-ray pulsars are neutron stars in binary systems accreting from a companion. The source of luminosity of these objects, reaching million solar luminosity, is the gravitational energy of the accreting matter. Accretion onto a compact object is a well known astrophysical process studied since early seventies.

If the companion is massive the mass transfer occurs via the capture of the stellar wind by the neutron star. If the companion is of low mass the stellar wind is not significant. In this case mass transfer occurs by the Roche lobe overflow. In this case the companion star fills its Roche lobe either by swelling at an evolutionary stage or as a result of the shrinking binary separation as a consequence of energy loss from the system. The overflowing matter is transferred to the lobe of the neutron star through the first Lagrange point. The inflowing matter, as it carries angular momentum, can not directly hit onto the neutron star; instead it forms a disk. Mass transfer takes place by the matter loading onto the magnetosphere and then onto the polar caps of the neutron star.

The interaction between the magnetosphere of a star with a surrounding accretion disk is a common theme in astrophysics. Disk accretion onto magnetic central objects occurs in a variety of astrophysical context involving accretion-powered X-ray pulsars. Numerous theoretical studies have been developed to understand the interaction between accretion disks and the magnetosphere of stars. One of them, proposed by Ghosh and Lamb in 1979 is the magnetically threaded disk (MTD) model which also forms the basis of this work.

An important ingredient of the disk-magnetosphere interaction is the torque acting on the star depending on the rotation rate of the star. In this thesis, this relation is determined from observational data of an accreting X-ray pulsar, 4U 1626−67.

In the first chapter, disk magnetosphere interaction is summarized with general equations.

The method that is used is explained in the second chapter. The method developed so as to eliminate all the parameters having uncertainty like mass of the accreting object and the distance.

In the third chapter, observational data of 4U 1626−67 is analyzed. This pulsar has a high magnetic field (approximately 10^{12} G) and is accreting from a low mass companion. As such it is identified as the most suitable source for determining the torque-rotation rate relation. This source underwent two torque reversals in June 1990 and February 2008. Also, application of the method is given in this chapter. Observational data belong to the 2008 reversal used in method.

The results are summarized in the fourth chapter. It's found that, the torque exerted on the star by the disk depends on the cube of the rotation rate near the torque equilibrium. Away from the equilibrium the torque-rotation rate relation is erratic. Also, a comparison of our model with the some of the existing models are given in this section.

In the last part of the thesis, the astrophysical significance of the results are discussed.

KÜTLE AKTARIMI YAPAN PULSARLARDA TORKUN GÖZLEMSEL OLARAK KISITLANMASI

ÖZET

X-ışını pulsarları ikili yıldız sisteminde yer alan ve eşlikçisinden kütle aktarımı yapmakta olan nötron yıldızlarıdır. Bu nesnelerin Güneş'in milyon katına ulaşan ışıma gücünün kaynağı nötron yıldızı üzerine düşen maddenin gravitasyonel potansiyel enerjisidir. Kompakt objeler üzerine diskten madde aktarımı astrofizikte çokça yer alan ve 1970'lerden beri üzerine çalışılan bir konudur. Eşlikçi yıldız büyük kütleli ise yıldız rüzgarları ile kaybettiği madde nötron yıldızı tarafından yakalanarak kütle aktarımı gerçekleşir. Eşlikçi yıldızın küçük kütleli olması durumunda ise rüzgar önemsizdir. Bu durumda kütle aktarımı Roche lob taşması ile gerçekleşir. Bu mekanizmada eşlikçi yıldız ya şişerek ya da yıldız çiftinin birbirine yaklaşması sonucu kendi Roche lobunu doldurur. Taşan madde yıldız çiftinin birinci Lagrange noktasından nötron yıldızının lobuna aktarılır. Gelen madde açısal momentuma sahip olduğundan nötron yıldızı üzerine doğrudan düşemez; nötron yıldızı etrafında bir disk oluşturur. Madde aktarımı bu diskten nötron yıldızının manyetosferine oradan da manyetik kutuplarına maddenin kanallanması yoluyla gerçekleşir.

X-ışını pulsarlarının 1971'de Giacconi ve arkadaşları tarafından keşfiyle beraber başlayan süreçte, bu nesnelerin periyot evrimleri yıllar boyunca gözlemlenmiştir. Bazı X-ışını pulsarlarının periyotlarının azalması aktarılan maddenin açısal momentumunu da yıldıza aktarmasının bir sonucu olarak anlaşılmıştır. Eğer nötron yıldızı çok hızlı dönüyor ise diskten gelen madde merkezkaç bariyeri nedeniyle nötron yıldızı üzerine düşemez, pervane mekanizması ile sistemden atılması söz konusu olabilir. Bu durumda disk-manyetosfer etkileşimi yıldıza yavaşlatıcı bir tork uygulayacaktır. Ancak pervane mekanizmasında yıldız üzerine madde aktarımı gerçekleşmediğinden X-ışını parlaklığı azdır.

Nötron yıldızının manyetosferi ve etrafındaki disk arasındaki etkileşimini ele alan ilk görüşler diskin sıcak, iyonize bir gazdan oluştuğundan yola çıkarak bu maddenin elektriksel iletkenliğinin yüksek olacağını ve diyamanyetik özellikler göstereceğini, yani manyetik alanı dışlayacağını öne sürmüşlerdir. Elbette diskin manyetosferi tam olarak dışlaması durumunda madde manyetosfere tırmanıp nötron yıldızı üzerine de düşemeyeceğinden X-ışını pulsarı oluşamayacaktır. Bu nedenle bu görüşü ortaya koyanlar X-ışını pulsarlarının gözlenmekte oluşunu da açıklayabilmek için diskin en iç noktasında manyetik alanın diske nüfuz edebildiğini varsaymışlardır. Ancak bu modele göre nötron yıldızına yavaşlatıcı tork etkiyorsa sistem pervane aşamasına geçmiş olmalı, X-ışını parlaklığı keskin biçimde düşmelidir.

Yavaşlamakta olan X-ışını pulsarlarının varlığını ve hızlanmadan yavaşlamaya geçerken X-ışını parlaklığında önemli bir değişiklik göstermeyen X-ışını pulsarlarının keşfedilmesini diyamagnetik disk modeli ile açıklamak imkansızdır. Bu gözlemleri

açıklamak için Ghosh ve Lamb 1979'da "manyetik olarak nüfuz edilmiş disk" modelini öne sürdüler. Bu modele göre kimi akışkan kararsızlıkları ve diskin zaten türbülanslı oluşu manyetik alanın diske nüfuz etmesini olanaklı kılacaktır. Yıldız ve diski birbirine bağlayan manyetik alan çizgileri açısal momentumun iletimini sağlamaktadır. Bu modele göre disk içine giren manyetik alanı beraberinde çekmekte ve böylece disk içerisinde torodial bir manyetik alan oluşturmaktadır. Korotasyon yarıçapı ötesinde bulunan manyetik alan çizgileri yıldızı yavaşlatırken, bu yarıçapın içinde bulunan manyetik alan çizgileri ise yıldızı hızlandırmaktadır. X-ışını pulsarı üzerine etki eden net tork kütle aktarımının sonucu olan hızlandırıcı maddesel tork ile hızlandırıcı ve yavaşlatıcı bileşenlere sahip manyetik torkun toplamı olacaktır.

Daha sonra yapılan kuramsal çalışmalar manyetik alanın çok geniş bir bölgede diske nüfuz etmesinin de mümkün olmayacağını ortaya koymuştur. Yıldıza göre oldukça yavaş dönmekte olan diskin dış kısımları, eğer alan bu bölgede diske nüfuz edebilseydi, öylesine büyük toroidal alanların üretilmesine yol açardı ki bu manyetik alanın basıncı o bölgede diskin dağılmasına yol açardı. Bu noktada ya alan çizgileri bu bölgelerde diske girmeyecek, girdiyse açılacak veya diskin alt ve üst düzlemindeki alanlar birbiriyle birleşerek yok olacaktır. Toroidal alanı kısıtlayan mekanizmanın hangisi olduğu anlaşılamamıştır. Ancak bu yıldız üzerine etkiyen torku belirleyen önemli bir parametredir.

Yıldızın uzun süreli spin evriminin anlaşılabilmesi bakımından yıldız üzerine etkiyen torkun yıldızın dönme hızına nasıl bir bağımlılığı olduğu önemlidir. Bu tez çalışması, yıldız üzerine etkiyen tork ve yıldızın dönme hızı arasındaki ilişkinin madde aktarımı yapan bir X-ışını pulsarının gözlemsel verileri ile belirlenmesini konu almaktadır.

Tezin ilk bölümünde, yıldızın manyetik alanı ve yıldızı çevreleyen disk arasındaki etkileşimin mekanizması MTD modeli bağlamında açıklanmış ve genel denklemler verilmiştir.

İkinci bölümde, yıldız üzerine etkiyen torkun yıldızın dönme hızına bağımlılığını açıklamak amacıyla geliştirilen metot açıklanmıştır. Metot, madde aktarımı yapan yıldızın kütlesi ve uzaklığı gibi belirsizliklere sahip olan tüm parametreleri sadeleştirecek şekilde geliştirilmiştir.

Üçüncü bölümde, tork-dönme hızı ilişkisini belirlemek için kullanılan kaynağın verileri analiz edilmiş ve metodun uygulaması gerçekleştirilmiştir. Çoğu yaşlı sistemler olan küçük kütleli X-ışını çiftleri, spin değişiminin gözlenmesini güçleştiren düşük manyetik alanlara sahiptir. Öte yandan genç ve yüksek manyetik alanlı nötron yıldızı içeren büyük kütleli X-ışını çiftleri ölçülen luminositeyi ve torku etkileyen yıldız rüzgarlarına sahip olduğundan dönme hızı-tork etkileşimini göstermek için uygun kaynaklar değildir. Dolayısıyla, yüksek bir manyetik alana (yaklaşık 10^{12} G) sahip olan ve düşük kütleli eşlikçisinden kütle aktarımı yapan 4U 1626-67 pulsarı en uygun kaynak olarak belirlenmiştir. Bu kaynak, Haziran 1990 ve Şubat 2008'de olmak üzere iki defa tork değişimi göstermiştir. 2008 tork değişimi civarında elde edilen periyot, periyot türevi ve akı verileri interpolarasyon ile çoğaltılarak açıklanan metot içinde kullanılmıştır.

Tezin dördüncü bölümünde, elde edilen sonuçlar sunulmuştur. Elde edilen sonuç Ghosh - Lamb modeli ve literatürde yer alan diğer modellerden birkaçıyla karşılaştırılarak grafiğe dökülmüştür.

Gözlemsel verilere dayanan modelin literatürde yer alan diğer teorik modellerden oldukça farklı olduğu görülmüştür. Literatür modelleri tork dengesi civarında aşağı bükey bir davranış ön görmektedir. Gözlemsel verilere dayanarak oluşturduğumuz modelde ise, diskin yıldız üzerine uyguladığı tork, tork dengesi civarında dönme hızının küpü olarak belirlenmiştir ve bu model yukarı-bükey davranış göstermektedir. Ayrıca, denge noktasının ötesinde ise, tork-dönme hızı ilişkisinin düzensiz olduğu görülmüştür.

Tezin son kısmında, sonuçların astrofiziksel önemi tartışılmıştır.

1. INTRODUCTION

X-ray pulsars are highly magnetized neutron stars accreting matter from a companion. The luminosity of the X-ray pulsar is the rate of gravitational potential energy released by accretion of matter onto the surface of the neutron star

$$L_{\mathrm{X}} = \frac{GM\dot{M}}{R} \tag{1.1}$$

where M is the mass, R is the radius of the compact object and $\dot{M}$ is the accretion rate. The matter in the disk rotates in Keplerian orbits

$$\Omega_{\mathrm{K}} = \sqrt{\frac{GM}{r^3}} \tag{1.2}$$

where r is the radial distance from the central object. At the inner boundary of the disk matter couples to the magnetic field of the star and accretes onto the polar caps.

Referring to the disk model, there are two main pictures regarding the interaction between magnetosphere and the disk. According to the first estimate, the disk is infinitely conducting so diamagnetic, and hence excludes the magnetic field. If the field was excluded totally we would never observe any X-ray pulsar as accretion would not be possible. Hence such models assume that the magnetic field penetrates the disk at the innermost region where matter is loaded onto the magnetosphere and channeled to the polar caps.

Accreting matter carries with it angular momentum. The spin up trend of the first discovered pulsars is understood to be the consequence of transfer of angular momentum along with mass to the accreting object. So the torque acting on the star by the disk is proportional to the mass accretion rate

$$N_{\mathrm{mat}} = \dot{M}\Omega_{\mathrm{K}}R_{\mathrm{in}}^2 \tag{1.3}$$

[1]. Discovery of X-ray pulsars with spin-down trend and those showing torque reversals led to the construction of the magnetically threaded disk model (MTD) by

Ghosh and Lamb in 1979 [2,3]. According to this model magnetic field of the neutron star threads the disk over a broad region. These field lines connecting the star and the disk cause angular momentum exchange in addition to the material torque given in Equation **1.3**.

As a result the magnetic fields transport angular momentum from the disk to the star or vice versa. While referring to the magnetosphere- disk interaction, a characteristic length is defined as corotation radius, R_c, where the Keplerian angular velocity in the disk equals to rotational angular velocity of the star defined as

$$R_\mathrm{c} = \left(\frac{GM}{\Omega^2}\right)^{1/3} \tag{1.4}$$

where Ω is the angular velocity of the star

$$\Omega = \frac{2\pi}{P} \tag{1.5}$$

and P is the rotation period.

The inner radius of the accretion disk, R_in, determined by the balance of material and magnetic stresses, and is conventionally expressed in terms of the Alfvén radius,

$$R_\mathrm{A} = \left(\frac{\mu^2}{\sqrt{2GM}\dot{M}}\right)^{2/7} \tag{1.6}$$

where magnetic energy density becomes equal to the kinetic energy density. The inner radius scales with the Alfvén radius as

$$R_\mathrm{in} = \xi R_\mathrm{A} \tag{1.7}$$

where ξ is a dimensionless number which is equal to 0.5 in the Ghosh-Lamb model and is larger in some other models. Here, μ is the magnetic moment of the star and is related to the magnetic field at the pole of the star, B, as

$$\mu = \frac{1}{2}BR^3. \tag{1.8}$$

Stellar field lines which couple to the disk outside of R_c will act to slow the rotation of the star down, while field lines which couple to the disk inside R_c will act to spin the star up. Accordingly, the net torque expended on the star by the disk is written as

$$N = I\dot{\Omega} = n\sqrt{GMR_\mathrm{in}}\dot{M} \tag{1.9}$$

where I is the moment of inertia and n is the dimensionless torque [2,3]. The fastness parameter is defined as

$$\omega_* \equiv \frac{\Omega}{\Omega_\mathrm{K}\left(R_\mathrm{in}\right)} = \left(\frac{R_\mathrm{in}}{R_\mathrm{c}}\right)^{3/2}. \qquad \mathbf{(1.10)}$$

The positive and negative torque contributions become equal at a critical fastness parameter, ω_c. This is where the torque reversals occur.

2. METHOD

In this chapter, the method used for obtaining the torque as a function of the fastness parameter will be explained.

Assuming a beaming fraction of b, the flux received is

$$F_{\mathrm{X}} = \frac{L_{\mathrm{X}}}{4\pi b d^2} \tag{2.1}$$

where d is the distance of the source. The mass flux onto the star then can be estimated as

$$\dot{M} = \frac{4\pi b d^2 F_{\mathrm{X}} R}{GM}. \tag{2.2}$$

Using Equation **2.2** and Equation **1.8** in Equation **1.7** the inner radius of the disk is found as

$$R_{\mathrm{in}} = \xi \left(\frac{B^2 R^5 \sqrt{GM}}{16\sqrt{2}\pi b d^2 F_{\mathrm{X}}} \right)^{2/7}. \tag{2.3}$$

The corotation radius can be shown in terms of the period as

$$R_{\mathrm{c}} = \left(\frac{GM}{4\pi^2} P^2 \right)^{1/3}. \tag{2.4}$$

Using the above two equations, the fastness parameter defined in Equation **1.10** can be written as

$$\omega_* = \xi^{3/2} \left(\frac{B^2 R^5}{16\sqrt{2}\pi b d^2} \right)^{3/7} \frac{2\pi}{(GM)^{2/7} F_{\mathrm{X}}^{3/7} P}. \tag{2.5}$$

So, the torque reversal occurs at a critical fastness parameter, ω_{c}

$$\omega_{\mathrm{c}} = \xi^{3/2} \left(\frac{B^2 R^5}{16\pi\sqrt{2} b d^2} \right)^{3/7} \frac{2\pi}{(GM)^{2/7} F_{\mathrm{c}}^{3/7} P_{\mathrm{c}}} \tag{2.6}$$

where P_{c} is the critical period and F_{c} is the corresponding flux. Dividing Equation **2.5** with Equation **2.6** we finally obtain

$$x \equiv \frac{\omega_*}{\omega_c} = \left(\frac{F_{\mathrm{X}}^{3/7} P}{F_{\mathrm{c}}^{3/7} P_{\mathrm{c}}} \right)^{-1} = \left(\frac{F_{\mathrm{c}}}{F_{\mathrm{X}}} \right)^{3/7} \left(\frac{P_{\mathrm{c}}}{P} \right) \tag{2.7}$$

which is devoid of all unknown parameters like B, d, M etc.

Equation **1.9**, using Equation **1.1** and Equation **2.3**, can be written as

$$-\dot{P} = n\omega_*^{1/3} \frac{4\pi b d^2 R}{(2\pi)^{4/3} (GM)^{1/3} I} F_{\mathrm{X}} P^{7/3} \qquad (\mathbf{2.8})$$

or by using Equation **2.7**

$$-\dot{P} = \frac{\omega_{\mathrm{c}}^{1/3} 4\pi b d^2 R F_{\mathrm{c}} P_c^{7/3}}{(2\pi)^{4/3} (GM)^{1/3} I} \frac{n}{x^2}. \qquad (\mathbf{2.9})$$

When the system is close to equilibrium the dimensionless torque can be approximated as $n = n_0(1-x)$ and so the equation above can be written as

$$-\dot{P} = C\frac{1-x}{x^2}, \qquad \text{for } x \simeq 1 \qquad (\mathbf{2.10})$$

where

$$C \equiv \frac{\omega_c^{1/3} 4\pi b d^2 R F_{\mathrm{c}} P_{\mathrm{c}}^{7/3} n_0}{(2\pi)^{4/3} (GM)^{1/3} I} \qquad (\mathbf{2.11})$$

is a constant. From the slope of $\dot{P}$ versus $\frac{1-x}{x^2}$, constant C can determined and plugged back into Equation **2.9** to find the above relation

$$\frac{n}{n_0} = -\frac{\dot{P}x^2}{C}. \qquad (\mathbf{2.12})$$

Several accreting pulsars show torque reversals in which they transit from spin-down to spin-up or vice versa. The critical period at which this occurs and the corresponding luminosity allow for a dimensionless scaling of the rotational state of the pulsar. Next chapter, we will try to determine the dimensionless torque acting on the pulsar 4U 1626−67 using observational data.

3. APPLICATION TO 4U 1626-67

In this Section, the observational data of the pulsar 4U 1626−67 will be analysed.

In order to describe the dimensionless torque applied by the disk on the star, the star should be a member of a low mass X-ray binary (LMXB) since the stellar winds occurring in high mass binaries (HMXB) can contribute the torque and the luminosity. Also, most of the LMXB are old and their magnetic fields are as low as 10^9 G which leads a smaller inner radius and weaker torque exerted on the star. As a result, their spin changes can hardly be observed. So, what we need is an object in low mass X-ray binary with high magnetic fields. The most suitable object for determining the value of dimensionless torque from the observations is identified as 4U 1626−67 which is an accretion-powered pulsar. It is discovered by Uhuru [4] in a low mass X-ray binary (LMXB) consisting of a 7.66 s X-ray pulsar [5] accreting from an extremely low mass companion (0.04 $M_\odot$).

From the pulse frequency history of 4U 1626−67, which is given in Figure A.1, two torque reversals occurred in 1990 and 2008 can be clearly seen. Period, spin-up rate and flux data [6] corresponding to the 2008 reversal are obtained by using the method explained in Chapter 2 and given in below figures.

In Figure 3.1, the period evolution of 4U 1626−67 near the 54500 MJD is given. The observational points are represented by dots [6]. In order to obtain more data points an interpolation method is used to smooth the data.

In Figure 3.2, the flux evolution of 4U 1626−67 in the same time interval is shown. The observational points are represented by dots [6] and the function is smoothed via interpolation.

In Figure 3.3, the period derivative evolution of 4U 1626−67 in the same time interval is shown. The observational points are represented by dots [6] and similarly, the function is smoothed via interpolation.

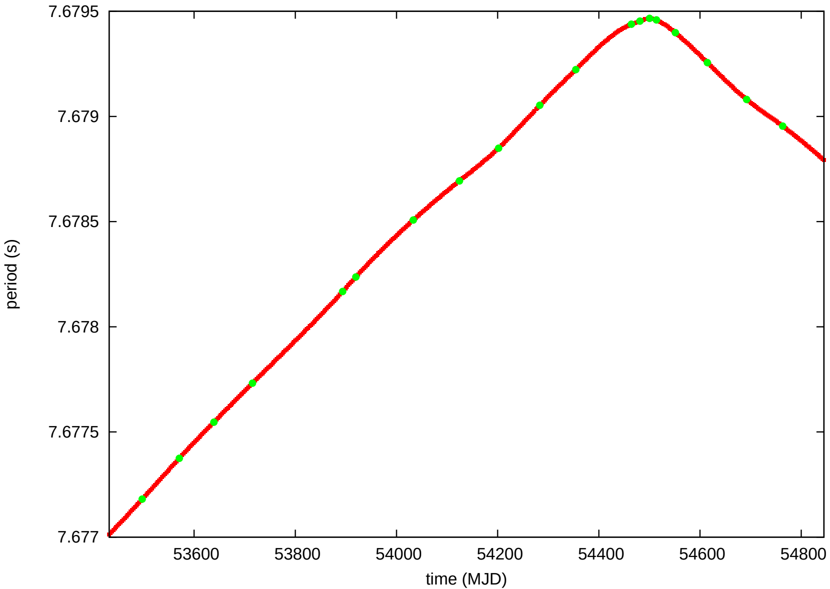

Figure 3.1: Period evolution of 4U 1626−67.

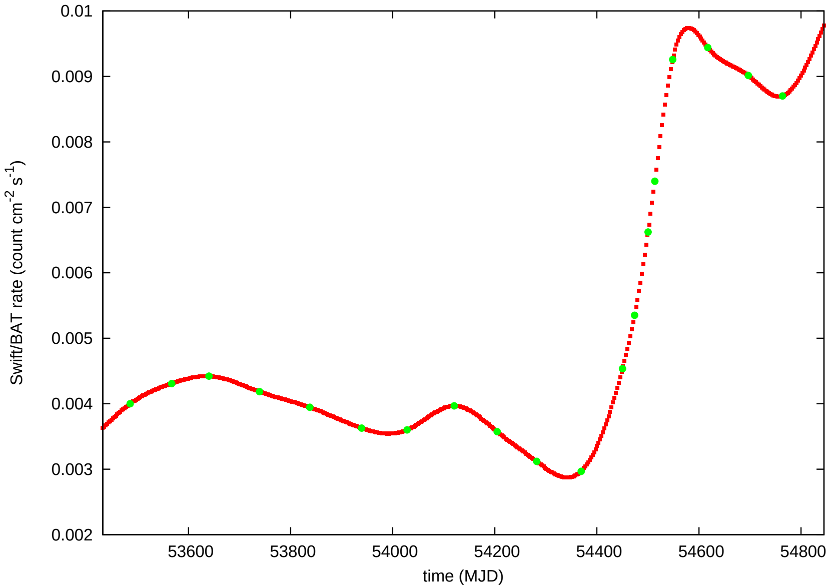

Figure 3.2: Flux evolution of 4U 1626−67.

Recalling Equation **2.6**, torque reversal occurs at a critical fastness parameter that is proportional to the critical period P_c and the corresponding flux F_c. As clearly seen from Figure 3.1 there is a torque reversal at a critical period $P_c = 7.6794662792$ s. Referring to Figure 3.2 flux corresponding to this critical period is determined as $F_c = 0.00658$ cnt cm^{-2} s^{-1}.

Using Equation **2.7** we have converted the above mentioned datas to a series of x values. We also have data series of $\dot{P}$ of the same time range as seen from Figure 3.3. Using this data series, parameter C can be easily obtained from the Equation **2.10**.

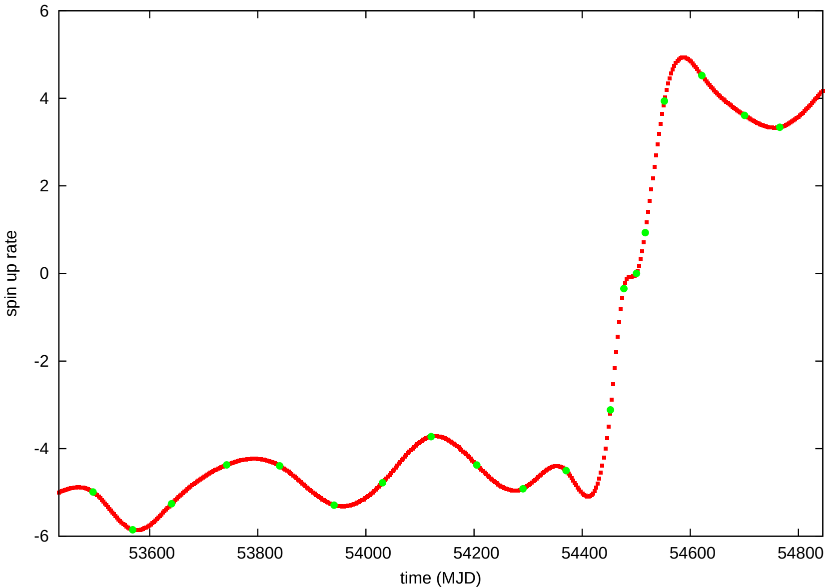

Figure 3.3: Spin-up rate ($\dot{\nu}$) evolution of 4U 1626−67.

Figure 3.4 shows the $\dot{P}$ versus $(1-x)/x^2$ graph. Red dots shows the C values. From the slope of $\dot{P}$ versus $\frac{1-x}{x^2}$, constant C can determined as $C = 9 \times 10^{-11}$ and plugged back into Equation **2.9**.

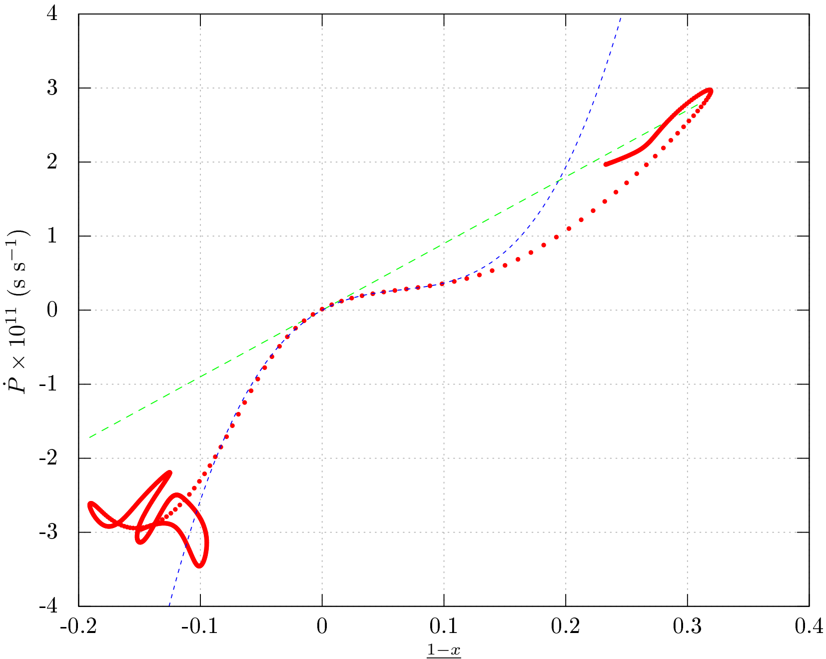

Figure 3.4: $\dot{P}$ versus $(1-x)/x^2$.

As explained in next chapter, we used this constant to determine the dimensionless torque via Equation **2.12**.

4. RESULTS

In this section, our results obtained by the method introduced in Chapter 2 will be presented.

In Figure 4.1 the dimensionless torque n scaled to $n_0 = -n'(1)$ versus fastness parameter ω_*, corresponding to torque equilibrium is shown. The points are obtained by manipulating the observational period, flux and period derivative data of the accreting pulsar 4U 1626−67.

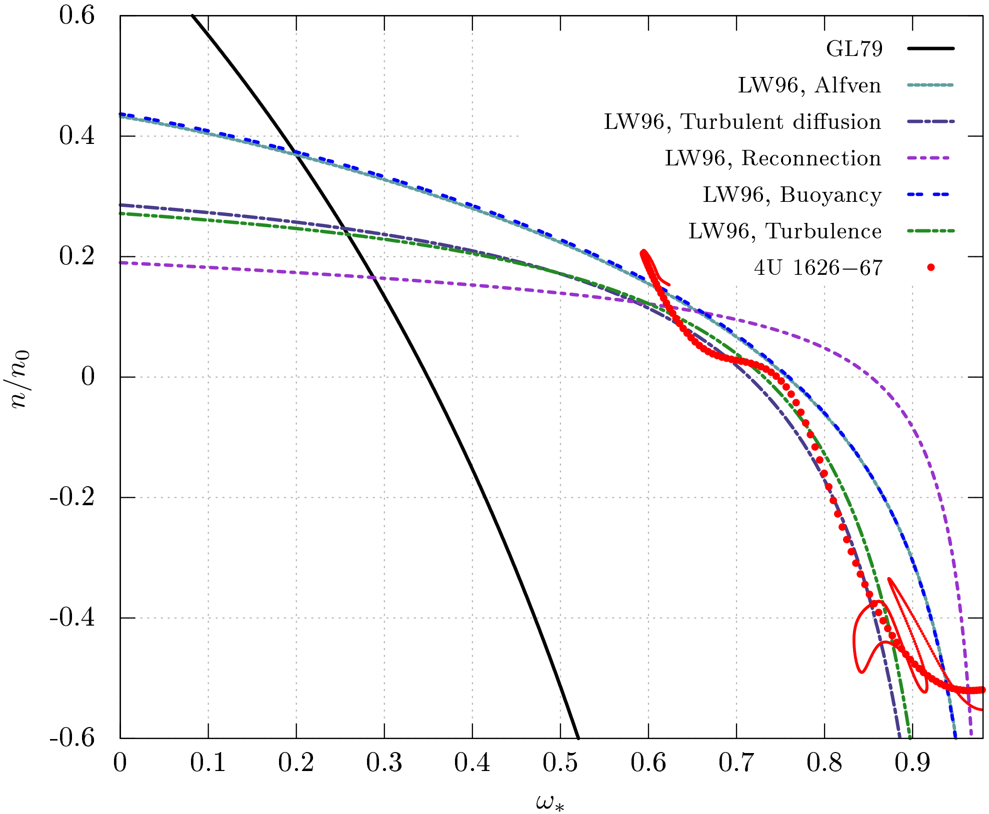

Figure 4.1: Dimensionless torque, n scaled to n_0 versus fastness parameter ω_* .

Comparison of the existing torque models [7] with the observationally constructed dimensionless torque can be seen in Figure 4.1. The torques selected from the literature are concave-down (convex) across the torque equilibrium whereas the torque we construct from the observational data of the accreting pulsar 4U 1626−67 can be described by a cubic function near the torque equilibrium

$$f(x) = a(x-1) + b(x-1)^2 + c(x-1)^3 \tag{4.1}$$

in the range $x = 0.9 - 1.1$ where we have fixed $a = -1$ and obtained $b = -11.4165 \pm 0.1444$ (1.265%) and $c = -50.3399 \pm 1.726$ (3.428%).

The torque models shown in the Figure 4.1 are listed in Table 4.1. The torques are obtained under different assumptions about the physics limiting the growth of the toroidal field in the disc generated by the differential rotation between the magnetosphere and the disc. Namely, turbulent diffusion, reconnection, Alfvén speed, buoyancy, and turbulence [7].

Table 4.1: Different torque models used in Figure 4.1.

$n(\omega_*) =$	phys.	ω_c	n_0
$1 + \frac{8}{9}\left(1 - \omega_* - \frac{(\omega_*)^{57/40}}{(1-\omega_*)^{1/2}}\right)$	Alf. sp.	0.76	4.3673
$\frac{(5/3)-(7/3)\omega_*}{1-\omega_*}$	turb. diff.	5/7	35/6
$\frac{(5/3)-(7/3)\omega_*+(4/9)\omega_*^2}{(1-\omega_*)}$	rec.	0.85	8.7728
$1 + \frac{8}{9}\left(1 - \omega_* - \frac{(\omega_*)^{35/24}}{(1-\omega_*)^{1/2}}\right)$	buo.	0.76	4.3242
$1 + \frac{20}{31}\frac{1-(31/16)\omega_*}{1-\omega_*}$	turb.	0.73	6.0567

According to the Ghosh-Lamb model the dimensionless torque is

$$n_{\mathrm{GL}} = 1.39 \frac{1 - \{\omega_*[4.03(1-\omega_*)^{0.173} - 0.878]\}}{1-\omega_*} \tag{4.2}$$

for which $\omega_c = 0.35$ [2,3]. In order to compare our result with the Ghosh-Lamb model we wrote $x = \omega_*/\omega_c$ and we plotted it as

$$\frac{n_{\mathrm{GL}}}{n_0} = 0.737 \frac{1 - \{\omega_c x[4.03(1-\omega_c x)^{0.173} - 0.878]\}}{1-\omega_c x}. \tag{4.3}$$

where $n_0 = -n'_{\mathrm{GL}}(1) = 1.8839$. The solid black curve in Figure 4.1 represents the Ghosh-Lamb model given in Equation (**4.2**)

5. DISCUSSION

In this thesis, we tried to establish the behaviour of dimensionless torque acting on the accreting pulsars in terms of the dimensionless fastness parameter. As indicated in the Chapter 2, MTD model seems to be most plausible picture to explain the magnetosphere-disk interaction. The torque we have found through an analysis of the data of X-ray pulsar 4U 1626−67 is qualitatively different than the existing MTD model torques in the literature.

Results that we achieve show that the dimensionless torque near the equilibrium is qualitatively different than the predictions of the existing models such as Ghosh-Lamb model. As shown in Figure 4.1, GL model is concave down whereas the result we found is concave up. According to our results the dimensionless torque has a cubic dependence on the fastness parameter.

Moreover, our results imply that beyond a critical value the dimensionless torque does not increase significantly but fluctuates and has an erratic dependence on the fastness parameter. We interpret the erratic behaviour at the end of the spin-down limit as an onset of the unstable regime that is expected to exist when the inner radius approaches the corotation radius. At this limit our assumption that the luminosity is linearly related to the accretion rate breaks down.

The erratic dependence of the torque on the fastness parameter at the slow-rotating limit is not well understood.

In order to understand the cubic dependence of the torque on the fastness parameter a theoretical study of disk-magnetosphere interaction is required. This is beyond the scope of this thesis which only demonstrate that an important ingredient is missing in MTD.

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APPENDICES

APPENDIX A.1 : Figure A.1

APPENDIX A.1

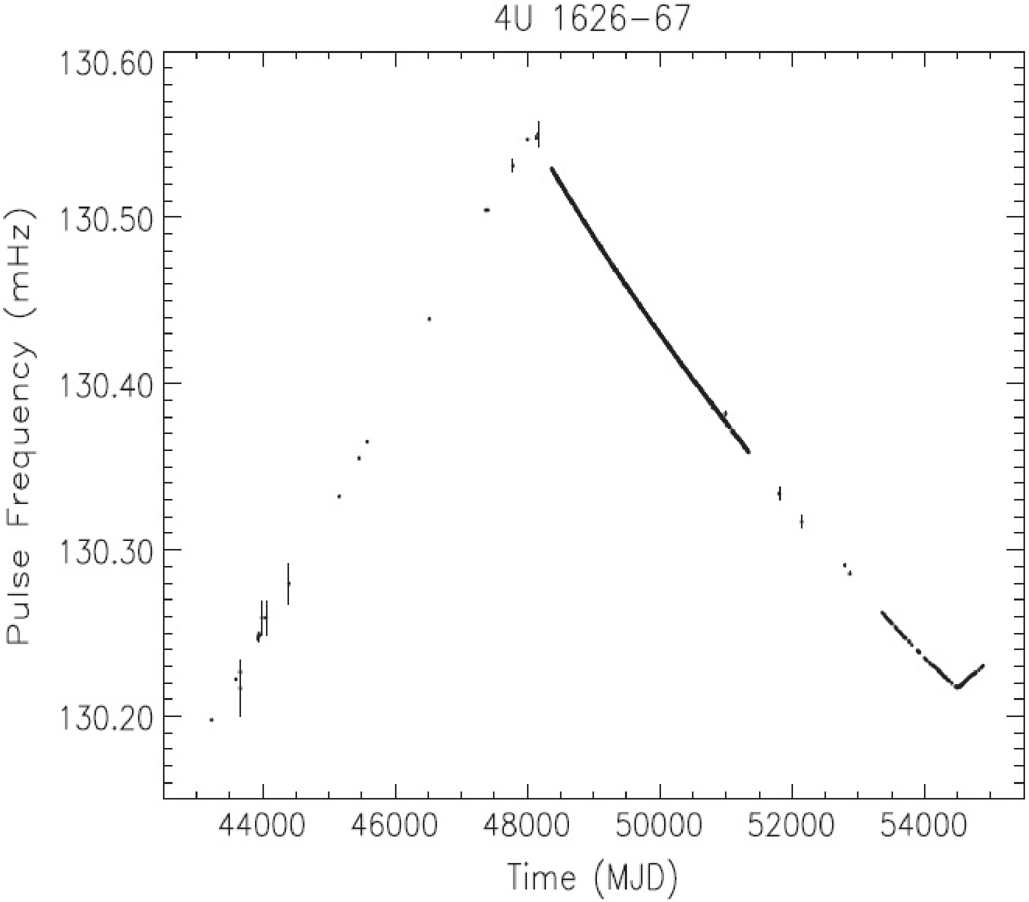

Figure A.1: Pulse frequency history of 4U 1626–67

Figure A.1 shows the pulse frequency history of 4U 1626–67 from 1997 up to 2009 [6]. The 1990 June and the 2008 February reversals are clearly seen.

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