

0.1 Defining the model

The rotation of a rigid body in the rotating reference frame is described by Euler's equations. To derive these, we begin with Euler's second law for the angular momentum \mathbf{L} in the inertial frame

$$\frac{d\mathbf{L}}{dt} = \mathbf{T}, \quad (0.1.1)$$

where \mathbf{T} is the applied torque. The angular momentum can be written as $I\boldsymbol{\omega}$, the product of the moment of inertia tensor and the spin vector. In the inertial frame both of these quantities vary in time; this does not lend itself to solving the equations. We can simplify solutions by transforming to a frame fixed in the rotating frame of the rigid body and aligning the axes with the principle axes of I . In such a frame the moment of inertia is constant and diagonal. The transformation to a rotating reference frame requires a modification of the time derivative in Euler's second law, see Landau and Lifshitz (1969) for details. The result is Euler's rigid body equations in the rotating frame:

$$\frac{d\mathbf{L}}{dt} + \boldsymbol{\omega} \times \mathbf{L} = \mathbf{T}. \quad (0.1.2)$$

To begin with, we will restrict ourselves to consider only biaxial bodies with principal moments given by

$$I_x = I_y = I_0 \quad I_z = I_0(1 + \epsilon_I), \quad (0.1.3)$$

where I_0 is the moment of inertia for which we use a canonical value of

$$I_0 = \frac{2}{5}MR^2 \approx 10^{45} \text{ g cm}^2 M_{1.4} R^2. \quad (0.1.4)$$

Here we have defined the neutron star canonical mass $M_{1.4} = 1.4M_\odot$ and R , the neutron star radius. Equation 0.1.2 gives us three coupled ODEs for ω_x, ω_y and ω_z . In the torque-free case analytic solutions can be found as shown in section ??.

To model the spindown of a neutron star we include a the torque from a dipole m frozen into the star in the $\hat{\mathbf{x}} - \hat{\mathbf{z}}$ plane at an angle χ to the $\hat{\mathbf{z}}$ axis. Deutsch (1955) demonstrated such a dipole exerts a torque on the star which has two components. It is presented here in form found in Goldreich (1970).

$$\mathbf{T} = \frac{2R}{3c} I_0 \epsilon_A \omega^2 (\boldsymbol{\omega} \times \hat{\mathbf{m}}) \times \hat{\mathbf{m}} + \epsilon_A I_0 (\boldsymbol{\omega} \cdot \hat{\mathbf{m}}) (\boldsymbol{\omega} \times \hat{\mathbf{m}}), \quad \text{with} \quad \epsilon_A = \frac{m^2}{I_0 R c^2}, \quad (0.1.5)$$

where ϵ_A the magnetic deformation as defined by Glampedakis and Jones (2010). The magnetic deformation can be related to the surface magnetic field strength by

$$B_0 = \left(\frac{4\epsilon_A I_0 c^2}{R^5} \right)^{1/2} \quad (0.1.6)$$

The first term in the Deutsch torque is often referred to as the *spin down*, or *braking* torque. As this suggests it is responsible for the power law retardation of spin frequency and has an associated timescale τ_S . The second term is known as the *anomalous* torque which acts on a timescale τ_A . The three timescales (including the precession timescale) in this problem are then given by

$$\tau_P = \frac{2\pi}{\epsilon_I \omega}, \quad \tau_A = \frac{2\pi}{\epsilon_A \omega}, \quad \tau_S = \frac{3c}{2R \epsilon_A \omega^2}. \quad (0.1.7)$$

By considering the ratio $\tau_A/\tau_S \sim v/c$ where v is the equatorial velocity, we see that $\tau_A \ll \tau_S$. It is worth noting that the spindown timescale here is exactly the same as that given in equation (??).

We now have the basic components of our neutron star: a biaxial rigid body spun down by a dipole torque. In table 0.1.1 we list the spherical components of spin vector and magnetic dipole. This is done in a system of coordinates where the polar angle is that made with the \hat{z} axis and the azimuthal is the angle between the projection of the vector onto the $\hat{x} - \hat{y}$ plane, and the \hat{x} axis. A sketch is provided in figure 0.1.1 showing the projection onto the $\hat{x} - \hat{z}$ plane.

		Magnitude	Polar angle	Azimuthal angle
Spin vector	$\boldsymbol{\omega}$	ω	a	ϕ
Magnetic dipole	\boldsymbol{m}	m	χ	0

Table 0.1.1: Table of spherical components for the spin vector and magnetic dipole

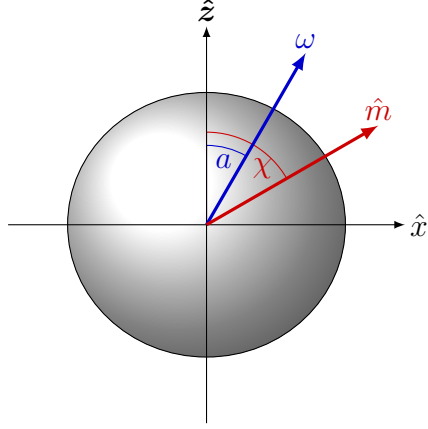


Figure 0.1.1: A sketch of the $\hat{x} - \hat{z}$ plane, the magnetic dipole lies solely in this plane such that its azimuthal component is always zero. Only the projection into this plane of the spin vector is shown, in general it has an azimuthal component given by ϕ .

We will now present results of this model found using numerical integration of (0.1.2) with the torque defined in (0.1.5). This is done for a NS with a magnetic field of $B_0 \approx 10^{13}$ G, and a radius $R = 10^6$ cm. We must also provide an initial condition for the angular frequency ω . This is not the spin frequency at the birth of NS but the frequency at the start of the observation; typical values are of the order ~ 10 rad/s. However, at this frequency the numerical solutions are computationally expensive. To reduce the time required to produce solution we will work with an initial frequency of $\omega = 10^4$ rad/s. This does not change the form of solution, only the timescales over which they evolve.

0.2 Spherical star

We begin by considering a spherical star with $\epsilon_I = 0$, such a star will not precess. This model was first considered by Davis and Goldstein (1970) and separately by Michel and Goldwire (1970); both sets of authors discovered that the spin axis aligns with the magnetic axis on the spindown

timescale. This is incompatible with the observation of neutron stars as NSs as we need the dipole to be misaligned with the spin axes to observe pulses.

We set $\chi = 30^\circ$ and $\epsilon_A = 5 \times 10^{-11}$ and plot the components of the spherical components spin vector in figure 0.2.1. This shows a brief spin down which halts once the spin vector aligns with the magnetic dipole $a \rightarrow \chi = 30^\circ$. The azimuthal angle ϕ does not vary, this is expected since precession, a monotonic increase in ϕ , does not occur for spherical bodies. This result agrees with the analytic calculations: the alignment occurs on the spin down time scale $\sim 3.6 \times 10^8$ s.

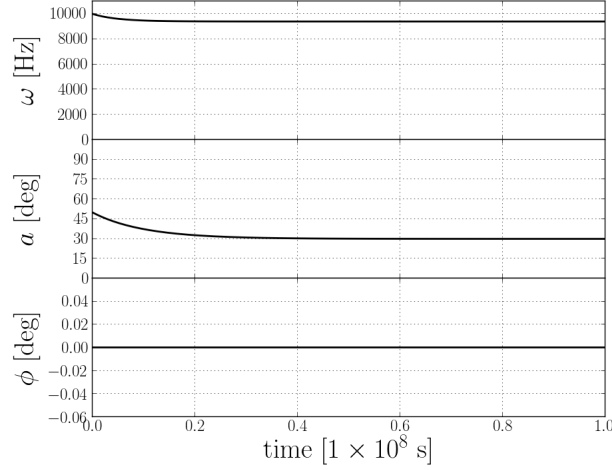


Figure 0.2.1: Plot of the spherical components of ω for a spherical star. Note that the magnetic dipole is inclined at $\chi = 30^\circ$ to the \hat{z} axis.

0.3 Biaxial NS with no anomalous torque

We begin with the evolution of the spin vector neglecting the anomalous torque. This reduces the number of timescales to just two, the spin down and the precession timescale. The solutions are categorised by the ordering of these time scales; it is shown in appendix 0.B that these orderings remain valid for the duration of the spindown. The ordering of the two timescales gives three different types of solutions corresponding to three regions:

$$\text{Regions A: } \tau_S > \tau_P \qquad \text{Region B: } \tau_S \sim \tau_P \qquad \text{Region C: } \tau_S < \tau_P \qquad (0.3.1)$$

Since all solutions in each region display the same behaviour, we pick three ‘neutron stars (NS)’ and list their parameters in table 0.3.1.

Phase space

The phase space of solutions is plotted in figure 0.3.1 parameterised by the elastic deformation ϵ_I and the surface magnetic field B_S which is given by (Shapiro and Teukolsky, 1983, p. 278)

$$B_S = \frac{2m}{R^3} \qquad (0.3.2)$$

	ϵ_I	ϵ_A	B_S [Gauss]	τ_S [s]	τ_P [s]
NS A	1.0×10^{-9}	0.5×10^{-10}	1.3×10^{13}	3.6×10^8	6.3×10^5
NS B	0.4×10^{-10}	0.5×10^{-10}	1.3×10^{13}	3.6×10^8	1.6×10^7
NS C	1.0×10^{-15}	0.5×10^{-10}	1.3×10^{13}	3.6×10^8	6.3×10^{11}

Table 0.3.1: Table of relevant values for the selected points. In calculating the Magnetic fields we have assumed canonical value of $R = 1 \times 10^6$ cm for the radius, and a value $\omega_0 = 1 \times 10^4$ rads s^{-1}

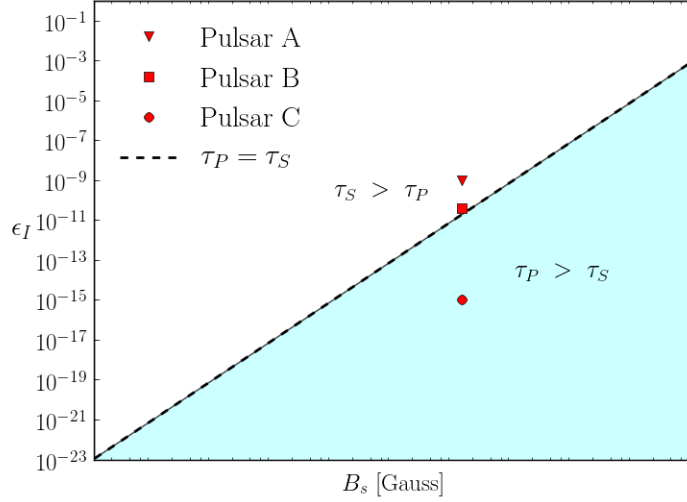


Figure 0.3.1: Phase space of solutions categorised by the ordering of the two timescales as a function of the elastic deformation ϵ_I and the surface magnetic fields B_s .

Without the anomalous torque the ordering of the timescales defines two distinct regions separated by $\tau_S = \tau_P$. In using an abnormally large value for the initial angular spin frequency ($\omega_0 = 10^4$ [rads/s]) we have skewed this phase space - that is, it no cannot be compared with the real pulsar population. Using a more realistic value the type of solution remains the same only the time scales vary.

The elastic deformation ϵ_I may take either a positive or a negative values; these correspond to either an oblate or prolate mass distribution. In all of the following we use only positive values of ϵ_I as these are thought to be more physical. It will be noted when this is thought to be important. Finally we must choose the angle between the magnetic dipole and the elastic deformations χ , because of the symmetry of the star about the \hat{z} axis we choose two values 30° and 75° to demonstrate important cases. Initial conditions are thought to have some bearing on the solutions (see Melatos, 2000). In the current work we will start with the spin vector having inclination angle of 50° and azimuth 0° .

0.3.1 NS A in region $\tau_S \gg \tau_P$

NSs in this region are described by the work of Goldreich (1970). In addressing the shortcomings of the analytic spherical solutions, Goldreich considered a neutron star with a solid crust capable of supporting elastic strains. In order to find an analytic solution Goldreich assumed that the

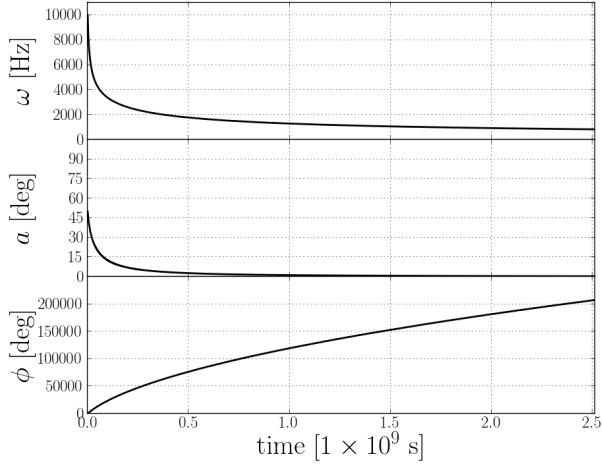
precession timescale was significantly shorter than the spin down timescale. Averaging equations (0.1.2) with this assumptions yields

$$\left\langle \frac{d\omega}{dt} \right\rangle = -\frac{2R}{3c} \epsilon_a \omega^3 \left[\sin^2 \chi + \sin^2 a \left(1 - \frac{3}{2} \sin^2 \chi \right) \right], \quad (0.3.3)$$

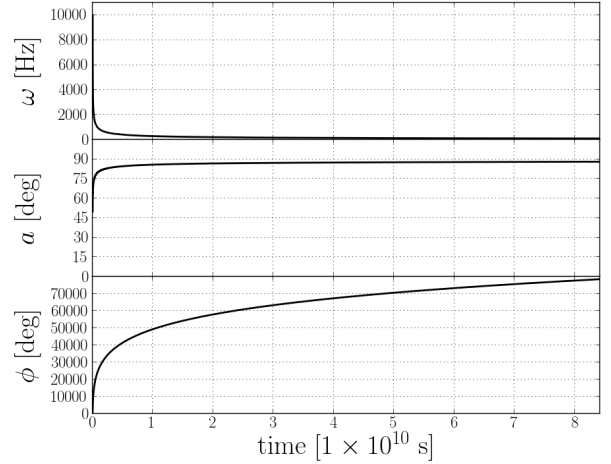
$$\left\langle \frac{da}{dt} \right\rangle = -\frac{2R}{3c} \epsilon_a \omega^2 \sin a \cos a \left(1 - \frac{3}{2} \sin^2 \chi \right). \quad (0.3.4)$$

These expression indicate that the polar angle a will either grow or decay on the spindown timescale depending on whether χ was greater or less than $\approx 55^\circ$.

We first present results for all the spherical components during the spindown in figure 0.3.2. For the angle χ we use two values 30° and 75° and find that a tends to either 0 or $\pi/2$ on the spindown timescale as suggested by Goldreich (1970). During this alignment, the spin magnitude decays and ϕ monotonically increases corresponding to the spin vector precessing about the \hat{z} axis.



(a) $\chi = 30^\circ < \chi_{cr}$

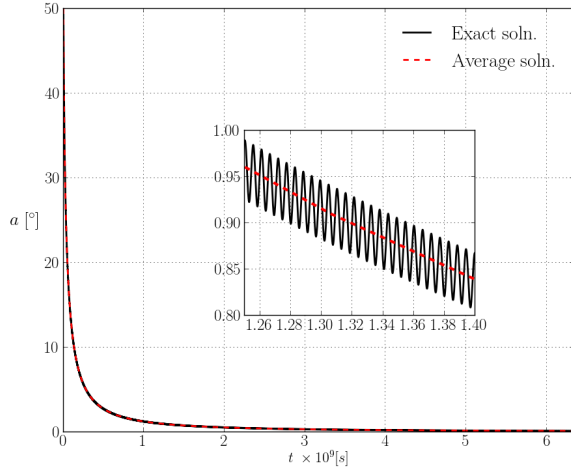


(b) $\chi = 75^\circ > \chi_{cr}$

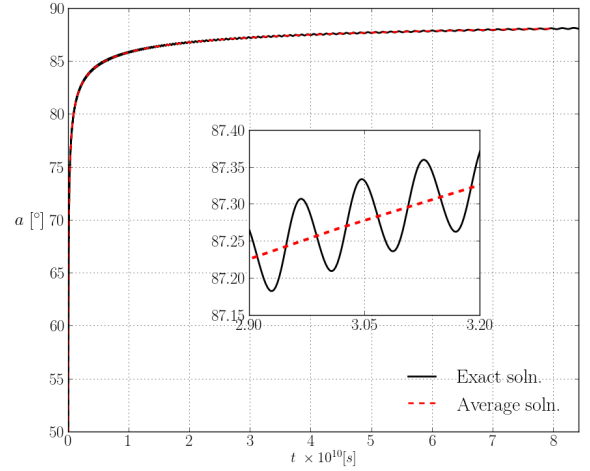
Figure 0.3.2: Plot of the spherical components of $\boldsymbol{\omega}$ for NS A. The two choices of χ allow us to confirm Goldreich's dependence of the alignment of the spin vector on χ .

We investigate the differences between Goldreich's averaged equations (0.3.4) and the exact solution without averaging in figure 0.3.3.

Our model agrees well with Goldreich's averaged result, but also exhibits oscillations due to precession.



(a) $\chi = 30^\circ < \chi_{cr}$



(b) $\chi = 75^\circ > \chi_{cr}$

Figure 0.3.3: Plot of the angle a for both the exact solution of (0.1.2) and the solution to the averaged equations (0.3.4).

A geometric argument To better understand the evolution of the spin vector and in particular the significance of $a \sim 55^\circ$ we introduce a geometric argument. Writing the conservation of energy and momentum in terms of the angular momentum vector J_i for a biaxial mass distribution we have

$$1 = \frac{J_x^2}{2I_x E} + \frac{J_y^2}{2I_y E} + \frac{J_z^2}{2I_z E} = \frac{J_x^2}{2I_0 E} + \frac{J_y^2}{2I_0 E} + \frac{J_z^2}{2I_0(1 + \epsilon_I) E}, \quad (0.3.5)$$

$$J^2 = J_x^2 + J_y^2 + J_z^2. \quad (0.3.6)$$

The first equation describes a biaxial ellipsoid with semi-axis given by $\sqrt{2I_0 E}$, $\sqrt{2I_0 E}$ and $\sqrt{2I_0(1 + \epsilon_I) E}$. The second describes a sphere of radius J . Both shapes are concentric with their origin at $\mathbf{0}$. Physical solutions require the conservation of both the energy and momentum, these solutions are therefore the intersection of the sphere and ellipsoid. This bounds the radius of the sphere by

$$2EI_0 < J^2 < 2EI_0(1 + \epsilon_I). \quad (0.3.7)$$

For a fixed energy and momentum, the intersection describes a circle about the $\hat{\mathbf{z}}$ axis. Several typical intersections are shown in figure 0.3.4. Points on the circle are the set of all possible solutions to the conservation equations for the angular momentum vector J_i . Since $J_i = I_{ij}\omega^j$ and the moment of inertia tensor is static, numerical solutions for the spin vector must also exist as points on a related circle. This related circle is exactly the precession of $\boldsymbol{\omega}$ about the $\hat{\mathbf{z}}$ axis.

Both the energy and the momentum decay exponentially in time due to the spindown. As a result both the sphere and ellipsoid will shrink, but not necessarily at the same rate. If we imagine observing the ellipsoid such that it appears to be fixed, we may see the sphere either shrink or grow with respect to the ellipsoid. We can parameterise the relative rate of shrinking by considering the quantity

$$A(t) = \frac{J^2}{2EI_0} \quad (0.3.8)$$

We could have chosen any one of the ellipsoids semi-axis since they are all proportional up to constants of ϵ_I . The evolution of the spin vector is related to the rate of change of A . This quantity determines whether the sphere shrinks or grows with respect to the ellipsoid. It is worth taking a moment to understand the different cases which are parameterised by the sign of \dot{A} :

1. $\dot{A} > 0$ The sphere grows with respect to the ellipsoid. In this case the intersection circles will ‘close up’ around the \hat{z} axis. This agrees with the solution for $\chi = 30^\circ$ given in figure 0.3.3(a). The angle between $\boldsymbol{\omega}$ and the \hat{z} axis tends to zero while ϕ monotonically increases. This describes the spin vectors following a circle about the z axis which gradually decreases in radius.
2. $\dot{A} < 0$ The sphere shrinks with respect to the ellipsoid. In this case the intersection circles will increase in radius until $J \rightarrow \sqrt{2EI_0}$. This describes exactly the solution in figure 0.3.3(b): that is $a \rightarrow 90^\circ$ while ϕ monotonically increases.

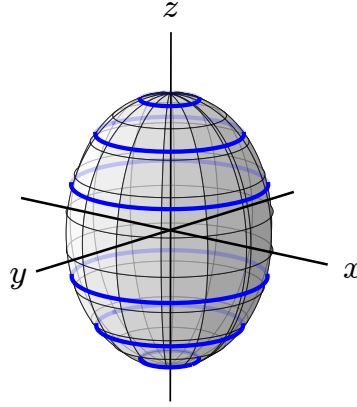


Figure 0.3.4: Intersection of the sphere and ellipsoid defined in equations (0.3.6) for three different values of M at fixed E . The sphere's of radius M are not visible, only the blue line shows where they would intersect the fixed ellipsoid.

Connecting with Goldreich's result In appendix 0.A we verify that the time averaged rate of change of A is given by the following.

$$\langle \dot{A} \rangle = \frac{1}{\langle E \rangle^2} I_0^2 \epsilon_I \omega^6 \frac{2R}{3c} \epsilon A \cos^2 a \sin^2 a \left(1 - \frac{3}{2} \sin^2 \chi \right) \quad (0.3.9)$$

This result is valid only in the regime for which $\tau_S \gg \tau_P$ and neglects the anomalous torque and term of order ϵ_I^2 . It demonstrates that only two factors determine the sign of \dot{A} : the sign of ϵ_I and the term $1 - \frac{3}{2} \sin^2 \chi$ giving a critical value $\chi_{cr} \approx 55^\circ$. The first we should expect on geometric grounds, a change in sign of the deformation changes the geometry of the ellipsoid. The second is in perfect agreement with the findings of G70, and shows that this critical value is a tipping point between the rates of change of energy and angular momentum.

Summary We find that, without the anomalous torque, the numerical model agrees well with analytic results in the literature. Further, we give an interpretation of the critical value of χ found by Goldreich (1970).

0.3.2 NS B in region $\tau_S \sim \tau_P$

Unlike the previous examples, there is no comparison in the literature which considers $\tau_P \sim \tau_S$ while neglecting the anomalous torque. This is primarily because the similarity of the timescales means simplifying assumptions cannot be made. The results have not been included here as they are exactly alike with the results of NS A, except the similarity of time scales means both the precession and alignment of the spin vector occur on the same timescale.

0.3.3 NS C in region $\tau_S \ll \tau_P$

In NS C the timescales take the ordering $\tau_P \gg \tau_S$. The limit of this region, is the spherical star ($\epsilon_I \rightarrow 0$) discussed in section 0.2; as such we should expect the results to be similar. Solving the equations of motion for NS C the spherical components of the spin axis are given in figure 0.3.5. Both choices of χ yield a similar result, the polar angle a tends to χ on the spin down timescale as anticipated by the likeness to the spherical star. In contrast the azimuthal angle ϕ appears to begin monotonically increasing before decreasing to a constant value. It is thought that this is due to the small but not vanishing magnitude of ϵ_I . In the perfectly spherical limit we observe no such increase in ϕ . Therefore the small deformation offsets the steady state solution of the spin axis from the magnetic dipole.

For an intuitive understanding consider that the torque acts to align the spin axis with the magnetic dipole; when this occurs the torque vanishes. Since the mass is not spherical, non-precessing solutions exist when the spin vector aligns with the principle axis of the moment of inertia tensor $\hat{\mathbf{x}}, \hat{\mathbf{y}}$ and $\hat{\mathbf{z}}$. So when both effects act, the steady state solution is an intermediary point between the two weighted by the relative strength of each effect. In this case the torque dominates and so the spin vector lies close, but not exactly aligned, with the magnetic dipole. During this time the star spins down but upon alignment the spin frequency asymptotically approaches a constant non zero value.

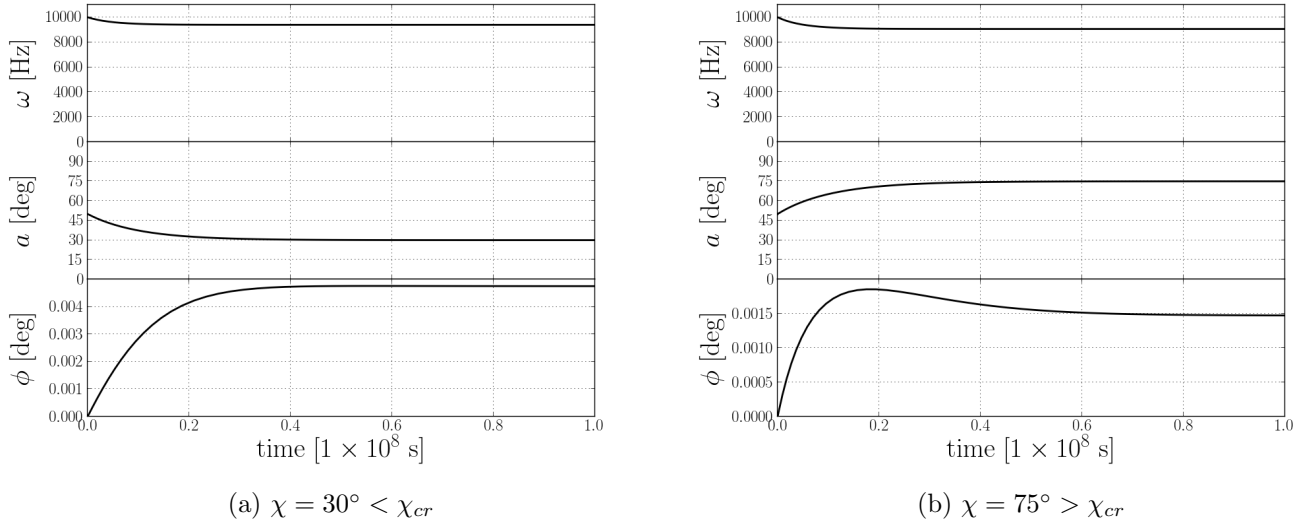


Figure 0.3.5: Plot of the spherical components of ω for NS C.

0.4 Biaxial NS including the anomalous torque

We now include the anomalous torque component in equation (0.1.2) and discuss the differences this makes to the numerical solutions. Before doing this we consider the appropriate reference frame in which to view the system.

0.4.1 Effective body frame

Working with a biaxial body and the Deutsch torque Melatos (2000) discovered non-trivial solutions where the spin axis aligns with an unknown angle between the magnetic dipole and the principle axis of the MOI. This was interpreted by Melatos as evidence for persistent precession. We show in section 0.4.1 that in fact the spin vector is aligning with another rotating reference frame that is held at a fixed angle to the original rotating reference frame. This reference frame, which we label the *effective* body frame is a result of the inclusion of the anomalous torque.

Writing equation (0.1.2) with the Deutsch torque we have:

$$\begin{aligned}
 J_{,t}^i + \epsilon^{ijk} \omega_j J_k &= N_{\text{spin down}}^i + \epsilon_A I_0 \omega^a \hat{m}_a \epsilon^{ijk} \omega_j \hat{m}_k, \\
 J_{,t}^i + \epsilon^{ijk} \omega_j (J_k - \epsilon_A I_0 \omega^a \hat{m}_a \hat{m}_k) &= N_{\text{spin down}}^i, \\
 J_{,t}^i + \epsilon^{ijk} \omega_j (I_{ka} - \epsilon_A I_0 \hat{m}_a \hat{m}_k) \omega^a &= N_{\text{spin down}}^i.
 \end{aligned}$$

By separating the equation this way and making use of $J_i = I_{ij} \omega^j$ we can write an effective moment of inertia tensor given by

$$I'_{jk} = I_{jk} - I_0 \epsilon_A \hat{m}_j \hat{m}_k, \quad (0.4.1)$$

$$= \begin{bmatrix} I_0(1 - \epsilon_A \sin^2 \chi) & 0 & -I_0 \epsilon_A \sin \chi \cos \chi \\ 0 & I_0 & 0 \\ -I_0 \epsilon_A \sin \chi \cos \chi & 0 & I_0(1 + \epsilon_I - \epsilon_A \cos^2 \chi) \end{bmatrix}. \quad (0.4.2)$$

Note we will use the prime to denote the effective body frame axis when quoting results. This effective moment of inertia tensor can be shown to have Eigenvalues given by

$$\lambda_2 = I_0, \quad \lambda_{\pm} = \frac{I_0}{2} \left(2 + \epsilon_I - \epsilon_A \pm \sqrt{\epsilon_A^2 + \epsilon_I^2 - 2\epsilon_A\epsilon_I \cos(2\chi)} \right). \quad (0.4.3)$$

If we diagonalise this effective moment of inertia tensor, these Eigenvalues are the diagonal entries, and the associated Eigenvector are the principle axis of the effective body frame axis. The Eigenvalues always take the ordering

$$\lambda_+ > I_0 > \lambda_-. \quad (0.4.4)$$

Defining the effective body frame axis by \mathbf{e}_i it is natural to associate the \mathbf{e}_2 of the effective body frame axis with the $\hat{\mathbf{y}}$ of the body frame axis such that they are always parallel. Since the other axis must be orthonormal, the transformation must consist of a rotation in the $x - z$ plane by an angle β . We are free to set the \mathbf{e}_3 axis to always take the largest Eigenvalue and then define β as the angle made by \mathbf{e}_3 with the $\hat{\mathbf{z}}$ axis. β is then given by:

$$\beta = \arctan \left(\frac{\mathbf{e}_{3,1}}{\mathbf{e}_{3,3}} \right) = \arctan \left(\frac{\epsilon_I - \epsilon_A \cos(2\chi) - \sqrt{\epsilon_A^2 + \epsilon_I^2 - 2\epsilon_A\epsilon_I \cos(2\chi)}}{2\epsilon_A \sin \chi \cos \chi} \right). \quad (0.4.5)$$

A schematic of the various angles and axis is given in figure 0.4.1

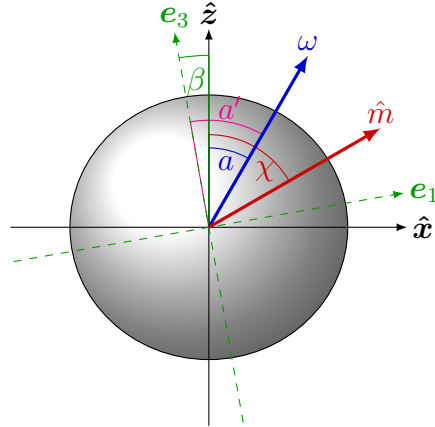


Figure 0.4.1: Schematic of the two sets of axis for an arbitrary β . Note that β is defined to be positive for a right hand rotation about the $\hat{\mathbf{y}}$ axis which is defined to be into the page.

Understanding the effective body frame The effective body frame is a simple rotation of the axis defined by the moment of inertia tensor to accommodate the effects of the anomalous torque. We work in a case where the rotation is in only the $x - z$ plane by an angle β .

To understand when this becomes significant we plot β as a function of $|\epsilon_A/\epsilon_I|$ in figure 0.4.2. When $|\epsilon_A| \ll |\epsilon_I|$, such that the anomalous torque effects are negligible, we recover the usual moment of inertia tensor. That is, $\beta = 0$ or $\beta = \pi/2$, dependent on the sign of ϵ_I . This is a consequence of choosing \mathbf{e}_3 to take the largest Eigenvalue. In the opposing limit $|\epsilon_A| \gg |\epsilon_I|$, in which the magnetic deformation dominates the sign of the elastic deformation no longer splits the solutions and both cases tend to $\chi - 90^\circ$. This means the effective body frame always aligns the \mathbf{e}_1 axis (which has the smallest Eigenvalue) with the magnetic dipole.

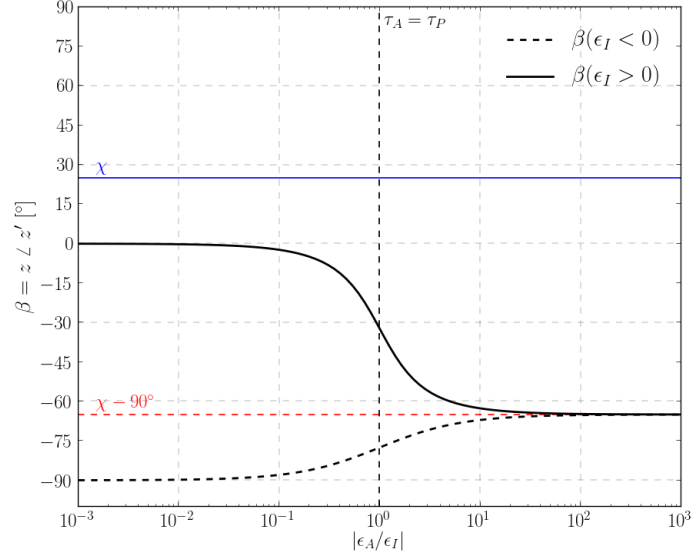


Figure 0.4.2: Plot of β as a function of the ratio $|\epsilon_A/\epsilon_I|$ for a prolate, $\epsilon_I < 0$ and oblate $\epsilon_I > 0$ mass distribution. In the limit $\epsilon_A \gg \epsilon_I$ for both the oblate and prolate cases the effective body frame aligns with the magnetic dipole. In the opposing limit the magnetic dipole has little effect and the effective body frame aligns with the principle axis of the moment of inertia. There is a smooth transition between these two extremes when $\epsilon_A \sim \epsilon_I$. The splitting into oblate and prolate solutions results from choosing to associate \mathbf{e}_3 with the largest Eigenvalue.

NS	ϵ_I	ϵ_A	B_S [Gauss]	τ_S [s]	τ_A [s]	τ_P [s]	$\beta(\chi = 30^\circ)$	$\beta(\chi = 75^\circ)$
A	1.0×10^{-9}	5×10^{-9}	1.3×10^{13}	3.6×10^8	1.3×10^7	6.3×10^5	-1.27°	-0.7°
B	0.4×10^{-10}	5×10^{-9}	1.3×10^{13}	3.6×10^8	1.3×10^7	1.6×10^7	-35.447°	-8.35°
C	1.0×10^{-15}	5×10^{-9}	1.3×10^{13}	3.6×10^8	1.3×10^7	6.3×10^{11}	-60.0°	-15.0°

Table 0.4.1: Table of relevant values for the selected points.

It should be made clear the rotation to the effective body frame is done in the post processing stage after the numerical ODEs are solved in the usual body frame. All three of our NSs have a non vanishing β , table 0.3.1 lists the relevant timescales and β for each NS.

Phase space

The introduction of the anomalous torque means we must also consider the anomalous torque timescale as given in equation (0.1.7). Three timescales can take six orderings. However, the spindown and anomalous timescale obey the following relation

$$\tau_S = \frac{3c}{2R} \frac{1}{\nu_0} \tau_A. \quad (0.4.6)$$

The coefficient $2R/3c$ effectively measures the importance of special relativity at the surface of the star. Since we expect $c \gg R\omega_0$ this means that only three physical orderings exist:

1. Region A: $\tau_S > \tau_A > \tau_P$
2. Region B: $\tau_S > \tau_P > \tau_A$
3. Region C: $\tau_P > \tau_S > \tau_A$

We can therefore update the phase space of possible solutions with the additional anomalous timescale; the result is given in figure 0.4.3.

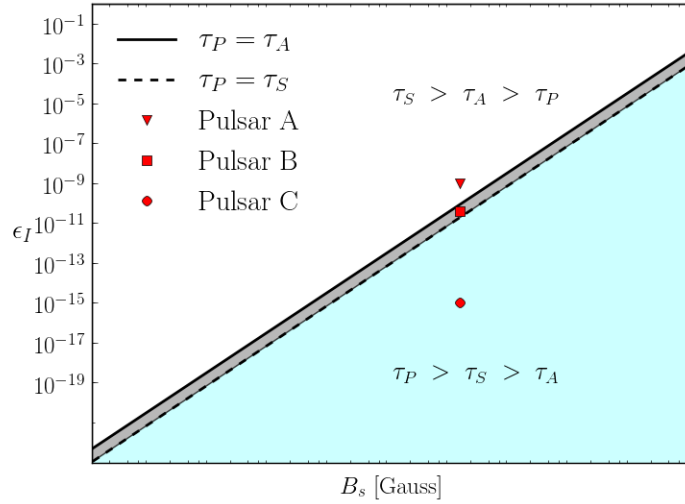


Figure 0.4.3: Phase space diagram including the anomalous torque contributions.

NS A in region $\tau_S > \tau_A > \tau_P$

We expect the alignment of the spin axis to agree with the findings in section 0.3.1 and study the changes in behaviour due to the introduction of the anomalous torque. Working in the effective body frame axis rotates the solutions by a few degrees as shown in table 0.4.1. Plotted in figure 0.4.4 are the spherical components of the spin vector in the effective body frame axis. This can be compared with the result in figure 0.3.2 which is the same system without the anomalous torque.

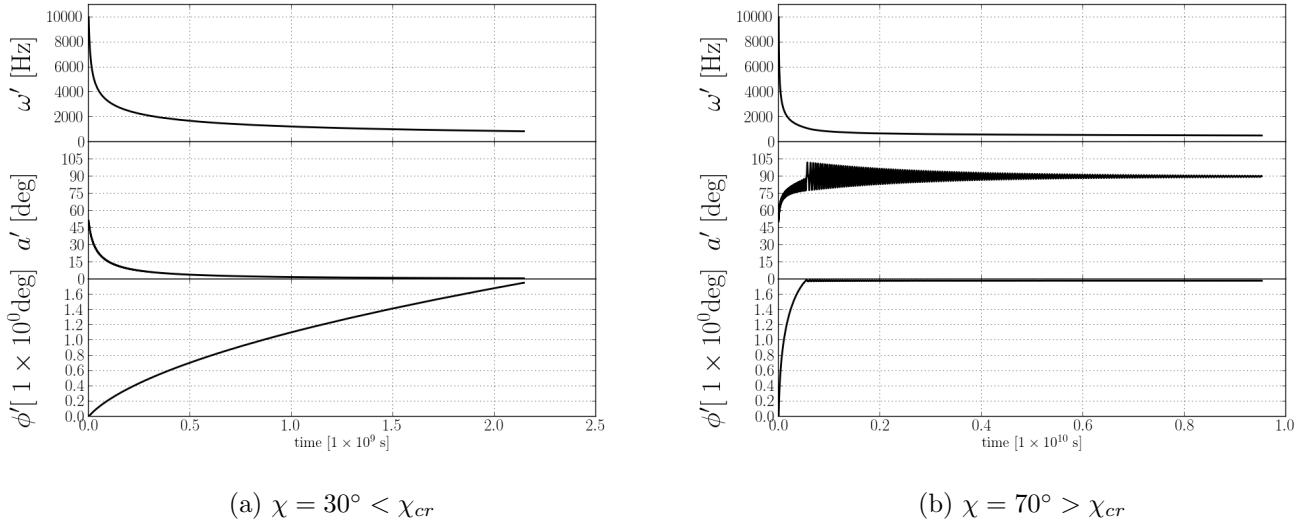


Figure 0.4.4: Plot of the spherical components of the spin vector during the spin down of NS A.

The final state alignment agrees well with results neglecting the anomalous torque for both values of χ . For $\chi = 30^\circ$ the intermediate behaviour appear similar to those shown in section 0.3.1. For $\chi = 75^\circ$ we have what appears to be a large discontinuity in the solution suggesting a significant difference between solutions when including the anomalous torque. To understand the cause of this, we return to the geometric argument made in section 0.3.1

A geometric argument Working in the effective body frame for which the effective moment of inertia tensor is triaxial. The conservation of angular momentum and conservation of energy are given by

$$1 = \frac{J_1^2}{2\lambda_- E} + \frac{J_2^2}{2I_0 E} + \frac{J_3^2}{2\lambda_+ E}. \quad (0.4.7)$$

$$J^2 = J_1^2 + J_2^2 + J_3^2. \quad (0.4.8)$$

The conservation of angular momentum describes an ellipsoid with semi axis given by $\sqrt{2\lambda_- E}$, $\sqrt{2I_0 E}$, and $\sqrt{2\lambda_+ E}$. The conservation of energy describes a sphere of radius J and for physical solutions the radius of the sphere is bounded by

$$2E\lambda_- < J^2 < 2E\lambda_+. \quad (0.4.9)$$

For a fixed energy and angular momentum we now have three distinct types of intersections as drawn in figure 0.4.5. We can now relate the three types of intersections to three types of solutions for the spin vector.

- (a) $2E\lambda_- < J^2 < 2EI_0$ In this region curves form two sets of complete loops around the \mathbf{e}_1 axis. As $J^2 \rightarrow 2E\lambda_-$ the intersection loops will close up about the \mathbf{e}_1 axis.
- (b) $J^2 = 2EI_0$ A special case in which the intersection forms two closed ellipses
- (c) $2EI_0 > J^2 > 2E\lambda_+$ In this region curves form two sets of complete loops around the \mathbf{e}_3 axis. As $J^2 \rightarrow 2E\lambda_+$ the intersection loops will close up about the \mathbf{e}_3 axis.

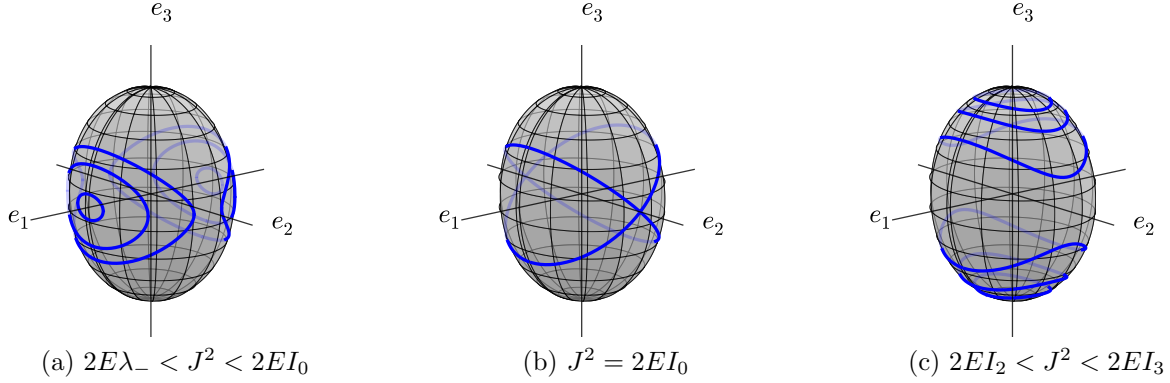


Figure 0.4.5: Intersection of the sphere and ellipsoid defined in equations (0.4.7) and (0.4.8) respectively.

All simulations begin in the same initial state. As previously observed, changing χ through the critical value changes the sign of \dot{A} and hence whether the sphere will grow or shrink with respect to the ellipsoid. So for $\chi = 30^\circ$ the sphere grows with respect to the ellipsoid ($\dot{A} > 0$) ending up with the loops closing up about the \mathbf{e}_3 axis. For $\chi = 75^\circ$ the sphere shrinks with respect to the ellipsoid ($\dot{A} < 0$) ending up with the loops closing up about the \mathbf{e}_1 axis. The two end states are then the (a) and (c) pictures in figure 0.4.5.

If they both begin from the same initial configuration, then one of them must pass through the special $J^2 = 2EI_0$ state corresponding to figure 0.4.5. When this happens, we will observe a change in the axis about which the solution precesses.

Both sets of solution start with the solution precessing about the \mathbf{e}_3 axis (ϕ monotonically increasing) corresponding to figure 0.4.5(c). In figure 0.4.4(b) the discontinuity is in fact exactly the point when the solution changes the axes of precession.

To better understand this, we plot the data from the $\chi = 75^\circ$ simulation (0.4.4(b)) in figure 0.4.6. Firstly in (a) we project the spherical components onto the unit sphere and choose three short sections of data. This shows that at early times, in blue, the solution precesses about the \mathbf{e}_3 axis. During the discontinuity, in red, the solution shows similarities with the $J^2 = 2EI_0$ case from figure 0.4.5. Finally at late times, in black, the solution precesses about the \mathbf{e}_1 axis. In figure 0.4.6(b) we also plot the solution in 3D during the apparent discontinuity. This again shows the solution goes through a change of the axis about which it precesses.

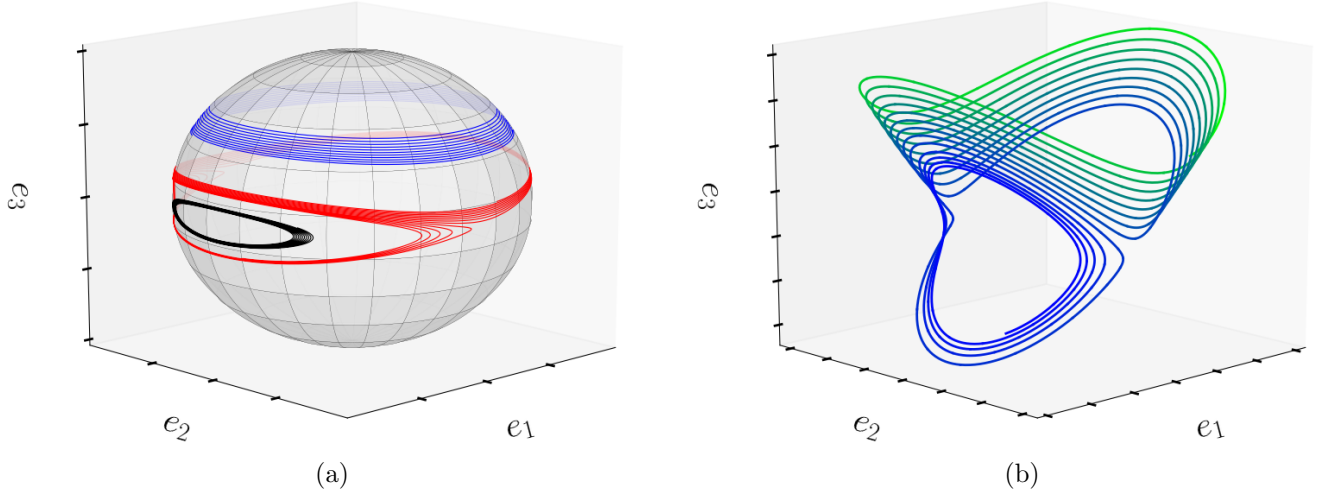
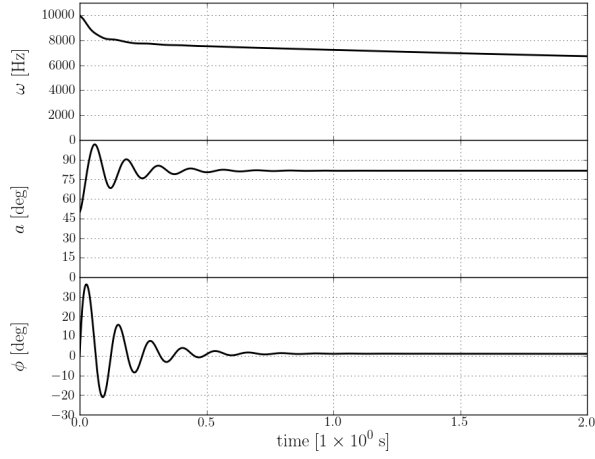


Figure 0.4.6: Numerical solutions for NS A plotted on the unit sphere in the body frame axis. (a) shows three distinct time steps: blue, the time before the discontinuity, red is during the discontinuity and black is some time after. (b) demonstrates the solution during the discontinuity, the changing colour is used to illustrate the evolution with time.

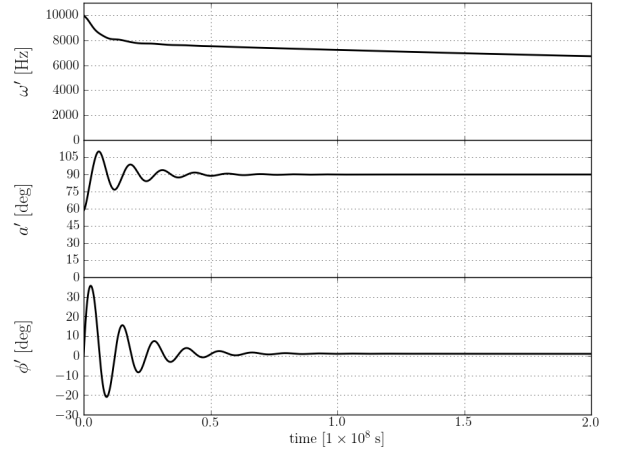
NS B in region $\tau_S > \tau_P > \tau_A$

This NS takes on a new significance having included the anomalous torque: we can now make a comparison with the work of Melatos (2000). In this work, Melatos found that when the precession timescale and anomalous torque timescales are comparable the solution admits persistent precession. This was defined as the polar angle a tending to a constant non-zero value with the nutation amplitude (oscillations in a) either decaying or remaining constant. Because the spin vector has not aligned with a principle axis of the moment of inertia this was interpreted as the spin vector undergoing persistent precession. Working in the body frame axis we confirm that $a \neq \pi/2$ at the end of the evolution in figure 0.4.7(a).

Transforming to the effective body frame in figure 0.4.7(b) we find that the spin vector in fact aligns with the principle axis of the effective moment of inertia ($a \rightarrow \pi/2$). Therefore the persistent precession angle found by Melatos is precisely the angle β . The spin vector has therefore aligned with the principle axis of the effective moment of inertia tensor associated with the smallest Eigenvalue. Since the azimuthal angle is constant, we argue that this is not persistent precession: the moment spin vector aligns with the effective body frame at which point the precession ceases.



(a) In the body frame axis

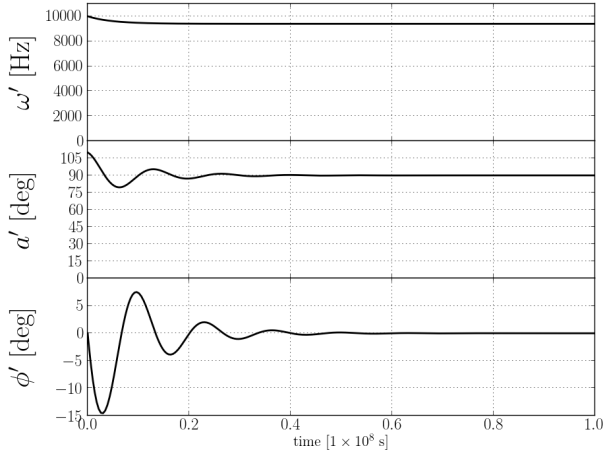


(b) In the effective body frame axis

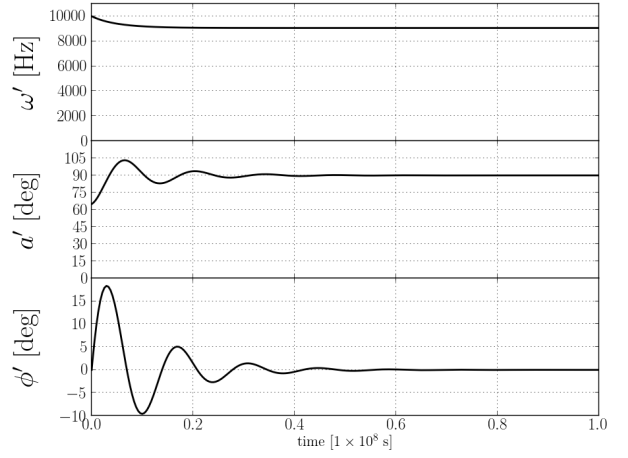
Figure 0.4.7: Plot of the spherical components of $\boldsymbol{\omega}$ for NS B

NS C in region $\tau_P > \tau_S > \tau_A$

In figure 0.4.8 for all values of χ the spin vector is found to align with the effective body frame \mathbf{e}_1 axis. In this limit ($\epsilon_A \gg \epsilon_I$ and so from figure 0.4.2) we see that the \mathbf{e}_1 axis aligns with the magnetic dipole. This agrees with the results for a spherical star in which $\epsilon_I \rightarrow 0$. The addition of the anomalous torque introduces oscillations on the anomalous torque timescale.



(a) $\chi = 30^\circ < \chi_{cr}$



(b) $\chi = 75^\circ > \chi_{cr}$

Figure 0.4.8: Plot of the spherical components of $\boldsymbol{\omega}$ for NS C.

0.4.2 Conclusion: Alignment of the spin vector

This simple model, comprising an elastic body supporting a biaxial strain and acted on by an electromagnetic torque, has been validated against known analytic results. Neglecting the anomalous torque we expand on the results of Goldreich (1970): the dependency on χ of the spin vector alignment is related to the ratios of angular momentum and energy.

When using the anomalous torque we introduce the effective body frame. In all cases we find that the spin vector aligns with the principle axis of the effective moment of inertia tensor. For NSs in region A of figure 0.4.3 the effective moment of inertia tensor is triaxial. This means that it is possible for the spin vector to precess about either of the principle axis associated with the smallest and largest Eigenvalue. As a result solutions can admit apparent discontinuities, under inspection these are revealed as the points where the precession changes between the two axis.

0.A Goldreich's result

Starting with

$$A = \frac{M^2}{2EI_0}, \quad (0.A.1)$$

and differentiating

$$\dot{A} = \frac{1}{(2EI_0)^2} \left(\frac{d}{dt}(M^2)2EI_0 - \frac{d}{dt}(2EI_0)M^2 \right), \quad (0.A.2)$$

simplifying and writing in index notation we have

$$\dot{A} = \frac{1}{E^2} \left(2M^i \dot{M}_i E - \dot{E} M^i J_i \right). \quad (0.A.3)$$

Now $E = \frac{1}{2}I_{ij}\omega^i\omega^j$, $\dot{E} = T^i\omega_i$ and $\dot{M}^i = T^i$, and so

$$\dot{A} = \frac{1}{E^2} \left(M^i T_i I_{jk} \omega^j \omega^k - T^i \omega_i M^j J_j \right). \quad (0.A.4)$$

For a diagonalised matrix, I_{ij} has only 3 non zero components and so $I_{jk}\omega^j\omega^k = (I\omega)_j\omega^j$. In addition $M^i = (I\omega)^i$ and so writing

$$\dot{A} = \frac{1}{E^2} T^i \left((I\omega)_i \omega_j - \omega_i (I\omega)_j \right) (I\omega)^j, \quad (0.A.5)$$

$$\dot{A} = \frac{1}{E^2} T^i \omega_i \omega_j (I\omega)^j (I^i - I^j). \quad (0.A.6)$$

Considering for the time being only the last few terms and expanding the summation it is clear all $i = j$ terms will be zero. Working with a biaxial mass distribution where $I_1 = I_2$, then the only non-zero terms are given by

$$\begin{aligned} T^i \omega_i \omega_j (I\omega)^j (I^i - I^j) &= T_1 \omega_1 I_0 (1 - \epsilon_i) \omega_3^2 (I_0 - I_0 (1 + \epsilon_I)) + T_2 \omega_2 I_0 (1 - \epsilon_i) \omega_3^2 (I_0 - I_0 (1 + \epsilon_I)) \\ &\quad + T_3 \omega_3 (I_0 (1 + \epsilon_I) - I_0) (I_0 \omega_1^2 + I_0 \omega_2^2), \\ &= I_0^2 \epsilon_I \omega_3 (T_3 (\omega_1^2 + \omega_2^2) - \omega_3 (1 + \epsilon_I) (T_1 \omega_1 + T_2 \omega_2)). \end{aligned}$$

Working up to 1st order in ϵ_I and inserting the spherical polar coordinates and then the spindown torque (we neglect the anomalous torque here) we have

$$= I_0^2 \epsilon_I \omega^3 \left(\frac{2R}{3c} \epsilon_A \omega^3 \right) \cos a \left([\sin \chi \cos \chi \sin a \cos \phi - \sin^2 \chi \cos a] \sin^2 a \right. \\ \left. - \cos a ([\sin \chi \cos \chi \sin a \cos \phi - \sin^2 \chi \cos a] \cos \phi \sin a - \sin^2 a \sin^2 \phi) \right).$$

Of course to know the exact behaviour, one would need to fully solve the original ODEs. To show agreement with Goldreich's result, we can assume that ϕ varies much faster than a and ω such that $\tau_P \ll \tau_S$. Then averaging over a free nutation period and neglecting the coefficients for the time being

$$\sim \cos a \left(-\sin^2 a \cos a \sin^2 \chi + \frac{1}{2} (\sin^2 a \cos a \cos^2 \chi + \sin^2 a \cos a) \right) \\ \sim \cos^2 a \sin^2 a \left(1 - \frac{3}{2} \sin^2 \chi \right).$$

Finally putting all the terms together we have an expression for the averaged rate of change of A with respecting Goldreich's assumptions:

$$\langle \dot{A} \rangle = \frac{1}{\langle E \rangle^2} I_0^2 \epsilon_I \omega^6 \frac{2R}{3c} \epsilon_A \cos^2 a \sin^2 a \left(1 - \frac{3}{2} \sin^2 \chi \right) \quad (0.A.7)$$

0.B Considerations for the timescales

We have used the ordering of the three timescale at $\omega_0 = \omega(t=0)$ to categorise the results. However, clearly the magnitude of the spin vector will decrease and the different dependencies on the spin vector could cause a 'crossing' of the timescales producing unexpected results. Writing the timescales then as

$$\tau_P(t) = \frac{2\pi}{\epsilon_I \omega(t)}, \quad \tau_A(t) = \frac{2\pi}{\epsilon_A \omega(t)}, \quad \tau_S(t) = \frac{3c}{2R} \frac{2\pi}{\epsilon_A \omega(t)^2}. \quad (0.B.1)$$

Only τ_S could cross with the other two timescales since the spin down and anomalous timescales obey $\tau_S > \tau_A$ provided that

$$\omega(t) > \frac{3c}{2R}.$$

This condition is satisfied by setting the initial rotational spin frequency at less than $\omega_0 \sim 10^4$ [Hz rad], that is the star should not break special relativity. At later times the spin frequency will decay and so this condition is still satisfied.

For the anomalous torque and precession timescale crossings two cases exists: either the deformations are such that the spin down timescale is larger than the precession initially (region A and B) or, as in region C, the precession timescale is larger than then spin down timescale. Considering the first case:

$$\tau_S > \tau_P \Rightarrow \omega(t) < \frac{3c}{2R} \frac{\epsilon_I}{\epsilon_A}. \quad (0.B.2)$$

In this particular state $\epsilon_I > \epsilon_A$ and so as in the previous case while the spin vector decays this inequality is always satisfied and the orderings remain the same. In the other case we have:

$$\tau_P > \tau_S \Rightarrow \omega(t) > \frac{3c}{2R} \frac{\epsilon_I}{\epsilon_A}. \quad (0.B.3)$$

In this case it is possible for the time scales to cross at $\omega_{cr} = \frac{3c}{2R} \frac{\epsilon_I}{\epsilon_A}$. For pulsar C this corresponds to a rotational spin frequency of 0.9 [Hz rad] which is four orders of magnitude smaller than the initial frequency. For this reason we can rule out this crossing of the time scales as an important factor in calculations.

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