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Tidal Interactions in Pulsar Binaries

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Abstract. The value of using pulse timing to measure orbital variations in eccentric pulsar binaries which are close enough at periastron to interact tidally is discussed. We briefly review a model for dynamical tidal evolution which shows that chaotic orbital evolution is possible, and list several applications to real systems. The system PSR J0045–7319 is then discussed, and a possible explanation for its decreasing orbital period is suggested.

1. Introduction

Observations of eccentric binaries which are close enough to interact tidally can reveal details of the stellar structure of the star suffering tidal deformation via measurments of the rate of apsidal advance. Pulsar binaries which "cleanly" interact tidally at periastron[1] offer the opportunity of measuring other orbit details with great precision. These include dynamical and secular changes in orbital eccentricity and orbital period due to the tidal interaction and tidal dissipation, as well as more details about the stellar structure via higher order apsidal motion (central condensation) parameters.

The non-zero eccentricity of some pulsar binaries in the field is a result of the kick the neutron star receives at birth. While most neutron star binaries are disrupted by this process ($\sim 70 - 80\%$ with low mass systems being more easily disrupted; Brandt & Podsiadlowski 1995), those which remain intact tend to be those for which the progenitor binary was rather tightly bound, leaving a pulsar binary which is close at periastron. Eccentric pulsar binaries containing non-compact companions which are close enough to interact tidally must necessarily contain young pulsars since they have not already circularized. Thus the chances of observing such systems are small.

Globular cluster pulsar binaries contain very old neutron stars which have been spun-up to observability by accretion from a companion. Such binaries may not be primordial, with dynamical processes such as tidal capture and exchange being responsible for their existence (Mardling 1995a,b, Aarseth & Mardling, this volume). Dynamical processes can also be responsible for the non-zero eccentricity of some of these millisecond pulsar binaries (Heggie & Rasio 1995), providing a potential source of eccentric pulsar binaries with non-

[1]The pulsar does not interact with the wind of the companion and hence remains observable during the time of maximum tidal distortion.

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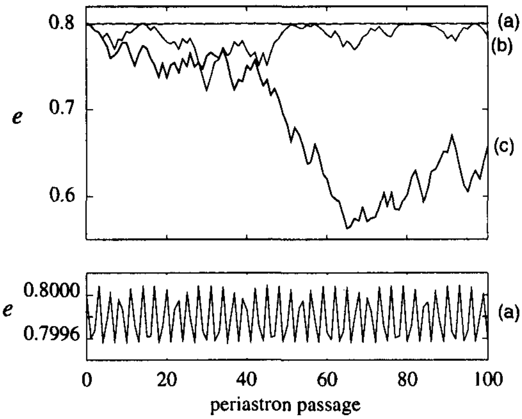

Figure 1. Chaos vs. periodicity. Curve (a) (shown magnified at the bottom of the figure) is typical of a periodic orbit for which the eccentricity varies little and the tidal energy is small. In contrast, curves (b) and (c) display the extreme sensitivity to initial conditions typical of chaotic systems, with the eccentricity varying over a wide range and the tidal energy becoming very large.

compact companions. On the other hand, the local gravitational potential will tend to contaminate the timing data so that such systems may not be useful for obtaining stellar structure information.

2. Dynamical Tidal Evolution: Regular and Chaotic Orbits

I have recently shown (Mardling 1995a) that in the absence of dissipation, two types of orbital evolution are possible. For most binaries, the tide-orbit interaction results in a periodic variation in the eccentricity (and orbital period), while for a range of high eccentricities and close periastron separations, this interaction is chaotic. Figure 1 illustrates these two types of behaviour for binaries modelled by a polytrope of index 1.5 and a point mass with initial conditions (a): $R_p = 3.2R_*$, (b): $R_p = 2.9R_*$ and (c): $R_p = 2.90001R_*$, each with $e = 0.8$, where R_p is the periastron separation and e is the eccentricity. The model used to produce these is based on a normal mode analysis for which the total energy and angular momentum are conserved, thereby allowing energy to flow freely between the orbit and the tides in a self-consistent fashion. There are at least three ways in which a binary can become chaotic:

1. Binaries which form via tidal capture in clusters must all pass through a chaotic phase (Mardling 1995b).

2. The inner binary of a hierarchical triple configuration may have its eccentricity induced to the extent that it becomes chaotic if the outer orbit is highly inclined to the inner orbit.

3. It is possible that some binaries are kicked into the chaotic regime at the birth of a neutron star. Such binaries are those which just manage to avoid dissociation; clearly they must be rare.

It is not clear what the dissipative response of the star(s) is during the violent chaotic phase, although it is almost certain that nonlinear processes will play an important role, perhaps even to the extent that the chaotic behaviour is suppressed (Kumar & Goodman 1996). Consequently, this phase is expected to be short so that observing a chaotic binary is unlikely. Nonetheless, it is interesting to speculate how such a violent history may manifest itself in a binary which has passed through this phase. For instance, consider a neutron star - main sequence star pair which at some time *following* the formation of the neutron star suffered a chaotic phase. If mass loss plays an important role while a binary is chaotic, then seemingly "impossible" systems may exist which, given their reduced binding energy following mass loss, would almost certainly have been disrupted had the companion had its present mass at the birth of the neutron star. The system PSR B1718–19 in NGC 6342 may have had such a history.

2.1. Stellar Spin

This model does not allow for the development of bulk stellar rotation, although it does allow angular momentum to be transferred from the orbit to the tides (and back again) in a way such that the local vorticity remains zero. While it is possible to include the effects of rotation in an artificial way by specifying some spin rate (Kumar et al. 1995), the non self-consistent nature of the resulting equations of motion precludes a detailed examination of the effect of rotation on the orbital period (due to tidal effects[2]) because the error in the energy budget is much larger than the effect one is trying to measure. It will be necessary to develop this model to allow for arbitrary velocity fields in the equations of motion of the fluid star before the effect of stellar spin in systems such as PSR J0045–7319 (see next section) can be examined in the necessary detail.

3. PSR J0045–7319

Only one eccentric pulsar-main sequence star binary with a clean periastron passage which is close enough to interact tidally has been discovered so far. This is the system PSR J0045–7319 in the SMC (Kaspi et al. 1994 and Kaspi this volume) for which a spin-orbit coupling may be dominating any tidal effects. It does appear, however, that the orbital period is decreasing monotonically; this cannot be due to spin-orbit coupling which does not affect the orbital period and may instead be due to tidal effects. If it continues to decrease with time, this will tell us that the tidal dissipation rate is high[3] and consequently, that the tides are energetic and may in fact be responsible, at least in part, for the timing residual at periastron. On the other hand, if we believe that the characteristic age of

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[2]This analysis is adequate for examining the effects of spin-orbit coupling (Lai et al. 1995).

[3]It should be noted that this effect could be due to the hydrodynamical mechanism described by Tassoul (1987, 1988).

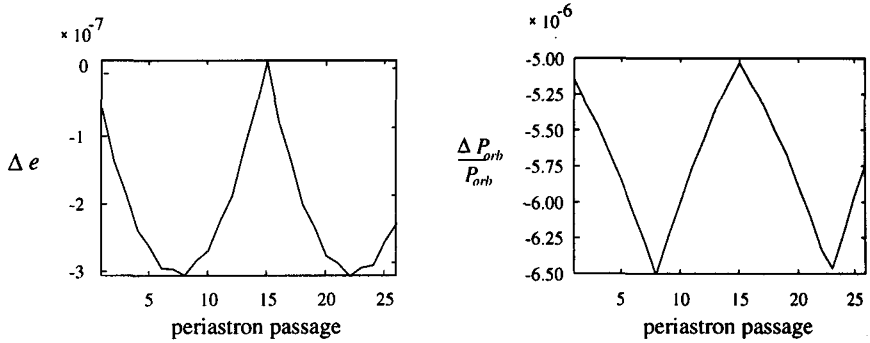

Figure 2. Example of a long-period variation in eccentricity and orbital period.

the pulsar (3 Myr) is representative of the true age, the dissipation rate implied by the rate of change of the orbital period is too high since it implies a pulsar age of around 0.5 Myr. An alternative explanation is that we are seeing the decreasing part of a long-term periodic variation in the orbital period resulting from dynamical tidal effects, as illustrated in figure 2. This model is a non-rotating polytrope - point mass pair ($n = 3$) for which the mass ratio is the same as PSR J0045–7319 ($M_B/M_{ns} = 6.3$), but $e = 0.1$ and $R_p = 5R_*$. It includes only f-modes with $l = 2$ and 3 (no g or p-modes) and shows how it is possible for the orbital period to decrease (or increase) approximately linearly for several orbits, mimicking the effects of strong tidal dissipation every half cycle. If the model is run with the parameters for PSR J0045–7319 ($e \simeq 0.8$, $R_p \simeq 4R_*$), behaviour similar to that shown in figure 1a is found. It is possible that including rotation (as well as g-modes) in a self-consistent way as discussed in the previous section would reveal a long-period variation in the orbital period for this system.

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